Long-Term Effectiveness of Cathodic Protection Systems on Highway Structures

PUBLICATION NO. FHWA-RD-01-096

JULY 2003

FOREWORD

Cathodic protection (CP), the technology used to mitigate corrosion of metals embedded in concrete, is the only rehabilitation technique that has been proven to stop corrosion in salt-contaminated bridge decks regardless of the chloride content of the concrete. This technology is based on the principle of applying an external source of current to counteract the internal corrosion current produced in reinforced concrete components. During CP, current flows from an auxiliary anode material through the electrolyte (concrete) to the surface of the reinforcing steel.

Various materials in various configurations are used as auxiliary anodes for CP resulting in various types of CP systems. The selection of the anode material and its configuration is paramount to the success of the system. The primary objective of this 5-year study was to determine the effectiveness of various materials and configurations when they are used as auxiliary anodes on highway structures during a long-term evaluation.

The findings of the study summarize the protection provided by the systems evaluated and estimate the expected service life for the anode materials in similar environments. This report will be of interest to engineers involved in bridge design, bridge performance evaluation and prediction, and bridge maintenance and rehabilitation.

T. Paul Teng

T. Paul Teng, P.E.
Director, Office of Infrastructure
Research and Development

Technical Report Documentation Page

1. Report No. FHWA-RD-01-096	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Long-Term Effectiveness of Cathodic Protection Systems on Highway Structures		5. Report Date July 2003
		6. Performing Organization Code
7. Author(s) Ali Akbar Sohanghpurwala and William T. Scannell		8. Performing Organization Report No.
9. Performing Organization Name and Address CONCORR, Inc. 44633 Guilford Drive, Suite 101 Ashburn, VA 20147		10. Work Unit No. (TRAIS) 3D4b
		11. Contract or Grant No. DTFH61-94-C-00054
12. Sponsoring Agency Name and Address Office of Infrastructure Research and Development Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101-2296		13. Type of Report and Period Covered Final Report August 1994 to July 1999
		14. Sponsoring Agency Code

15. Supplementary Notes

Technical Consultant: Donald Jackson, HIPA-20

16. Abstract

The Federal Highway Administration (FHWA) has concluded, on the basis of extensive research, that cathodic protection (CP), the technology used to mitigate corrosion of metals embedded in concrete, is the only rehabilitation technique that has proven to stop corrosion in salt-contaminated bridge decks regardless of the chloride content of the concrete. This technology is based on the principle of applying an external source of current to counteract the internal corrosion current produced in reinforced concrete components. During CP, current flows from an auxiliary anode material through the electrolyte (concrete) to the surface of the reinforcing steel.

Various materials in various configurations are used as auxiliary anodes for CP, resulting in various types of CP systems. The selection of the anode material and its configuration is paramount to the success of the system. The primary objective of this 5-year study was to determine the effectiveness of various materials and configurations when used as auxiliary anodes on highway structures during a long-term evaluation.

Twenty highway structures (19 bridges and 1 tunnel) protected by one or more CP system(s) were included in this study. The structures were located in 11 States and 1 Canadian Province. These structures were protected by a total of 19 impressed current and 5 galvanic CP systems. Most of the structures were selected by FHWA based on previous studies performed under the Strategic Highway Research Program (SHRP); this study was funded under the continuation of the SHRP program.

The findings of the study summarize the protection provided by the systems evaluated and estimate the expected service life for the anode materials in similar environments. On some structures, the systems were operated at insufficient output current and this resulted in poor performance. If these systems had been operated at higher output currents, their performance would have been rated higher.

17. Key Words Cathodic protection, corrosion, concrete rehabilitation, bridges, reinforcing steel, LTPP.	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 81	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	millimeters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
fl	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

TABLE OF CONTENTS

CHAPTER **PAGE**

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

LIST OF TABLES

EXECUTIVE SUMMARY

Cathodic protection (CP) is a technology used to mitigate corrosion of metals embedded in concrete. Based on extensive Government and private industry research, the Federal Highway Administration (FHWA) concluded that CP is the only rehabilitation technique that has been proven to stop corrosion in salt-contaminated bridge decks regardless of the chloride content of the concrete. This technology is based on the principle of applying an external source of current to counteract the internal corrosion current produced in reinforced concrete components. During CP, current flows from an auxiliary anode material through the electrolyte (concrete) to the surface of the reinforcing steel.

Various materials in various configurations are used as auxiliary anodes for CP, resulting in various types of CP systems. The selection of the anode material and its configuration is critical to the success of the system. The primary objective of this study was to determine the effectiveness of various materials and configurations when used as auxiliary anodes on highway structures during a long-term evaluation.

Twenty highway structures (19 bridges and one tunnel) protected by one or more CP system(s) were included in this study. The structures were located in 11 States and one Canadian Province. These structures were protected by a total of 19 impressed-current and 5 galvanic CP systems. The following types of systems were monitored for a period of 5 years:

1. Impressed-current:
    - (a) Arc-sprayed zinc
    - (b) Zinc stripes
    - (c) Titanium mesh
    - (d) Titanium ribbon
    - (e) Arc-sprayed titanium
    - (f) Conductive coating
    - (g) Conductive polymer slotted
    - (h) Conductive polymer mounded
    - (i) Conductive coke asphalt

2. Galvanic cathodic protection systems:
    - a) Arc-sprayed zinc
    - b) Expanded zinc mesh
    - c) Zinc foil with adhesive

Based on the age of the system, three to eight evaluations were planned for each structure. Most of the structures were selected by FHWA based on previous studies performed under the Strategic Highway Research Program (SHRP). Additional structures were added to the program as they became known to the research team. Structures that could not be properly evaluated were excluded from the study. This study was funded under the continuation of the SHRP program.

Findings

A summary of the findings of this study is presented in tabular form below. The first four columns provide information on the systems evaluated in this study. The fifth column provides a rating for the protection provided by the systems (i.e., excellent, good, fair, or poor). Based on the results of this study and the experience of the authors, an estimate of expected service life for the anode materials in similar environments is presented. In this summary, the protection provided by the system is based on the actual operation of the system. On some structures, the systems were operated at insufficient output current and this resulted in poor performance. If these system had been operated at higher output currents, their performance would have been rated higher.

Table 1. Summary of findings

Anode Material & Configuration	Environment	No. of Systems	Age of Systems (years)	Protection Provided	Estimated Service Life (years)
Impressed-current Cathodic Protection Systems					
Arc-sprayed zinc	Semi-marine & deicing	2	2	Poor[1]	10 to 15
Arc-sprayed zinc	Marine	1	1	Excellent	7 to 12
Arc-sprayed zinc	Deicing	1	8	Not determined[2]	10 to 15
Titanium mesh	Deicing	3	6 to 12	Excellent	>25
Titanium mesh	Marine	1	1	Excellent	>25
Titanium ribbon	Deicing	1	9	Excellent	15 to 25
Arc-sprayed titanium	Semi-marine & deicing	1	1	Poor[1]	Not determined[3]
Arc-sprayed titanium	Marine	1	1	Poor	Failed in 1 year
Conductive paint	Deicing	2	4 to 9	Good	5 to 10
Conductive polymer slotted	Deicing	1	12	Fair	5 to 10
Conductive polymer mounded	Deicing	1	15	Poor	5 to 10
Coke breeze	Deicing	3	5 to 9	Excellent	10 to 15
Galvanic Cathodic Protection Systems					
Arc-sprayed zinc	Marine	3		Excellent	7 to 10
Zinc foil with adhesive	Deicing	1	1	Excellent	7 to 10
Expanded zinc mesh & bulk	Marine	1	3	Good	15 to 20

(1) Systems operated at insufficient current output.
(2) No instrumentation installed to allow determination.
(3) System operated intermittently to allow proper evaluation.

2.0. TEST METHODS

In this study, standard test methods and generally accepted industry practices were used in evaluating the long-term performance of the CP systems. Under certain circumstances, some of the test methods and practices encountered problems with implementation and data interpretation. Although many of these issues are known to many users, very little discussion is found in literature. This chapter lists all test methods and practices used in this study and the problems encountered in their use.

Test methods and practices common to both the impressed-current and galvanic CP systems are discussed first. This is followed by a discussion of methods used for impressed-current CP systems and galvanic CP systems.

2.1. Test Methods: Impressed-current and Galvanic Systems

The following test methods and practices common to both the impressed-current and galvanic CP systems are described below.

2.1.1. Visual Survey

During each evaluation, a visual survey of the section of the structure or component protected by the CP system was performed. In some instances, a visual survey of control areas set up adjacent to the protected area was also performed. All signs of corrosion-induced damage, concrete deterioration, deterioration of anode material, and anomalies were documented. In some structures, access was insufficient to conduct a visual survey of the entire cathodically protected area. In such structures, visual survey was limited to accessible areas. Only the results of the visual survey that impact the long-term performance of the system being evaluated are discussed in this report.

2.1.2. Delamination Survey

Sounding techniques using a hammer or a chain were used to detect delaminations or disbondment of the protected surface. In many instances, overlays were present and the hollow-sounding areas detected could have resulted from corrosion-induced damage or disbondment of the overlay from the original concrete. When possible, cores were collected to differentiate between delamination and disbondment. The results of the delamination survey are not discussed in the report if no hollow-sounding areas were detected.

2.1.3. Electrical Continuity Testing

Three test methods that can be used to perform electrical continuity testing. The most commonly used technique is the direct current (DC) method. The other two techniques are alternating current (AC) measurement and the half-cell technique.

In the DC method, resistance and the voltage difference between two embedded metals are measured. When this technique was developed, there were concerns that the resistance measured could be impacted by currents flowing between the embedded metals. To overcome the impact of these currents, the method requires measurement of resistance in both directions. If no currents are involved and the meter is exclusively measuring DC resistance, the resistance in both directions would be equal. Under generally accepted criteria for the test method, it is required that the resistance measured in the two directions not differ by more than 1 ohm and the voltage difference between the two points not exceed 1 millivolt (mV). The maximum allowable value of the resistance measured in each direction is dependent on where the measurement is made. When the DC technique is used directly on exposed reinforcement, as is the practice during construction of the CP system or condition evaluation of the structure, the maximum allowable resistance in each direction is 1 ohm (some in the industry use a criterion of 3 ohms). When the technique is used in an installed CP system, and the wires connected to the system grounds and the grounds of instruments such as the reference cells, current probes, null probes are used for the resistance measurement, the maximum allowable resistance in the each direction is dependent on the run of the wires.

Although the basis for the evaluation criteria for this technique is very sound, there are exceptions, such as when this criterion fails to detect continuity. When currents generated by various sources such as corrosion cells or stray currents are present in the reinforcement system targeted for testing, the DC technique fails to detect continuity. The presence of these currents results in the measurement of resistance and voltage representative of the electrical network associated with the current and the resistance of the target embedded metals. This problem is most prevalent when electrical continuity measurements using this technique are made in structures that are cathodically protected, are experiencing very active corrosion, have the presence of stray currents, or have some internal source of current.

In this report, the primary concern is measuring electrical continuity of elements in cathodically protected structures that have been de-energized. When a CP system is de-energized, the cathodically protected reinforcement is depolarizing and trying to reach a stable state. In this condition, the DC technique is very prone to impact by currents generated during the stabilizing of the system. Some systems stabilize very quickly and DC electrical continuity measurements produce valid results within hours of the system's being de-energized, whereas some systems take more than 24 hours to fully stabilize. Also, after a system is de-energized, corrosion cells may be initiated, depending on the corrosiveness of the environment, resulting in corrosion currents' flowing in the target element. When anode materials such as zinc are used for impressed-current systems, if they are in contact with the steel, although the system is de-energized, they will form a galvanic couple with the steel and produce currents in the element that impact DC measurements.

At the start of this study, the DC technique was used exclusively to detect continuity of system grounds and the grounds of embedded instruments. As unexpected results were encountered, AC and half-cell techniques were used in addition to the DC measurements to ascertain the presence or lack of continuity.

In the AC technique, only one AC resistance measurement is made between the target elements. Similar to the DC technique, the maximum allowable AC resistance to signify the presence of continuity is dependent on where it is used. As AC currents are capable of shorting through discontinuities when an appropriate capacitance is generated across the discontinuity, the AC resistance measurement may incorrectly identify continuity when none exists.

The half-cell technique is based on the concept that a reference cell will measure the same potential (of the same target area) even when different grounds are used, as long as these grounds are electrically continuous. The technique requires that the potential of the target area not differ by more than 1 mV when various grounds are used to measure it in order for continuity to be present between the grounds used in the test. This technique works only if the potential of the target area is stable and not changing with time.

2.1.4. The AC Resistance Measurements

The AC resistance measurements between anode and system ground were used to obtain circuit resistance of the system and to detect the presence of shorts between the anode and the embedded steel protected by the CP system.

The AC resistance measurements between reference cells and their respective grounds were used to identify malfunctioning reference cells. When the AC circuit resistance is very high, it may be indicative of the failure of certain types of reference cells. High circuit resistance in conjunction with no response by a reference cell to changes in CP current indicates a malfunctioning reference electrode. High resistance also makes the reference cell prone to noise pick-up and makes the measurement of accurate potentials somewhat difficult.

The Ontario Ministry of Transportation, which developed the voltage probe, recommends the use of AC resistance measurement between the voltage probe and the system ground, as well as the voltage probe and the anode, to determine its reliability.

2.1.5. Chloride Ion Content Analysis

Core samples were collected from protected areas of the structures during one of the evaluations. Powdered concrete samples were collected from various depths in the cores and analyzed for total chloride ion content in accordance with the standard test method prescribed by the

American Association of State Highway and Transportation Officials (AASHTO) T-260[3], "Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials." The results of the chloride ion content analysis at the steel depth, when available, are presented in the text to provide some idea of the corrosivity of the environment in which the cathodic protection system was operating.

2.2. Test Methods: Impressed-current Systems

When the impressed-current systems were evaluated, the as-found operating parameters were documented first. These included measuring output voltage, output current, and back electro-magnetic force (BEMF). In most rectifiers, meters are provided to measure the output voltage and the output current. An external meter was used to verify the accuracy of the meters in each rectifier. The output settings of each zone in each rectifier evaluated were also documented. This was followed by the measurement of the instant-off potentials of all embedded reference cells and voltage probes present and of currents in current probes and null probes. After these measurements were recorded, the system was de-energized.

Once the system was de-energized, all anode, system ground, reference cell, reference cell ground, null probe, and current probe connections, as appropriate, were removed from terminals connected to the rectifier and the measuring instrument circuits. Subsequently, electrical continuity testing and AC resistance measurements were performed. The connections were removed from the rectifier and the instrumentation to ensure that the internal circuits of the rectifier and the instrumentation did not impact the results of the tests.

Upon sufficient passage of time after the system was de-energized, static potentials of all embedded reference cells and currents in the current probes and null probes were measured.

After all measurements were completed, the system was re-energized and rectifier operating parameters were documented. Adjustments to output current or other corrections were made, when necessary, to some systems for which permission had been obtained.

In some systems, during certain evaluations, one or more circuits were found to be powered off. In such instances, all data to be collected while the system was de-energized were collected and, when possible, the system was energized. Instead of measuring polarization decay, polarization development was measured.

2.2.1. Instant-Off Potential Measurement

There are several methods for measuring instant-off potentials in impressed-current systems using embedded or external reference cells. Many rectifiers are equipped with instrumentation to measure instant-off potentials. In this study, all instant-off potentials were measured using an external meter and one of the following two methods:

- Peak-hold method
- Manual current interrupt method

When possible, the accuracy of the rectifier instrumentation in measuring instant-off potentials was verified by comparing the measurements made using an external multimeter with measurements obtained with one of the methods listed above.

Before any measurements were made, an oscilloscope was used to identify the output waveform and detect the presence of electrical noise in the system. When necessary, the scope-null method was used to verify the data obtained by the peak-hold method. When noise was detected, an attempt was made to eliminate it by the use of capacitors. Sometimes we were successful in eliminating the noise. When noise was detected and could not be eliminated, the manual interrupt technique was used. Also, rectifiers with filtered outputs and no mechanism for interruption of the current required the use of the manual method.

2.2.1.1. Peak-Hold Method

In this technique, the ability of the multimeter to store the highest potential measured by a reference cell in a 1-millisecond (ms) window is used. The highest potential measured by a reference cell is expected to occur when the current in the CP system momentarily goes to zero. In a rectifier with unfiltered output, the output current goes to zero when the AC cycle reverses polarity. In a rectifier with a filtered output, an internal current interrupter is used to interrupt the current for a given period of time. The peak-hold function of the multimeter is used to measure the peak potential that signifies the instant-off potential of the reference cell.

2.2.1.2. Manual Current Interrupt Method

In the manual method, the output current of the rectifier is interrupted manually and the potential difference between the reference cell and the steel is measured 1 second after the power interruption using a multimeter.

2.3. Test Methods: Galvanic Systems

The evaluation of galvanic systems was performed by measuring the CP current generated by the anode and/or the polarization development and/or decay. The output current can be measured as a voltage drop across a resistor connected between the anode and the system ground or as a current density of a rebar probe. Polarization development and decay measurements are made using embedded reference cells, rebar probes, and/or external reference cells. The system must be equipped with a resistor or a rebar probe for the current measurement to be made.

Many galvanic systems are equipped with rebar probes. Rebar probes contain a piece of reinforcing steel with a known surface area that is embedded in the concrete element to be protected. The rebar probe is connected to embedded steel via a fixed resistor. The resistor allows the measurement of current received by the probe. When a switch or other mechanism is installed to allow the rebar probe to be disconnected or connected to the structural steel, it can be used for polarization development or decay measurement. When a rebar probe is used, the connection or disconnection of the rebar probe to the structural steel does not impact the system operation. In Florida, where galvanic systems are commonly used to protect marine bridge substructures, two rebar probes are often used adjacent to one another. At any time, one probe is connected to the reinforcing steel and the other is not. During evaluation, the connected probe is used to perform depolarization (polarization decay) testing and the other probe is used to perform polarization (polarization development) testing. When rebar probes are not installed, the system must be disrupted if polarization development or decay testing are done, and a mechanism must be available to disrupt the system.

3.0. ZINC-BASED IMPRESSED-CURRENT CP SYSTEMS

3.1. Arc-sprayed Zinc

A total of four arc-sprayed zinc-impressed-current CP systems were evaluated. Two of these, the Yaquina Bay Bridge and the Depoe Bay Bridge, were in a similar environment and the other two, the Queen Isabella Causeway and the Upper Salt Creek Bridge, were in a very different environment. Table 3-1 lists pertinent information on the four CP systems:

Table 3-1. Arc-Sprayed Zinc Impressed-current CP Systems

Structure Name and Location	Year CP System Installed	Element(s) Protected	Area Protected (m^2)	Instrumentation	Age at Last Evaluation	Average Chloride Ion Content at Steel Depth (ppm)*
Yaquina Bay Bridge, Newport, OR	1996	Super- and substructure elements	19,461 m^2	2 reference cells per zone	2 years	NA
Queen Isabella Causeway, South Padre Island, TX	1997	Tie beam & footings in bent	127 m^2	3 reference cells & 2 null probes	13 months	317 at center footing
Depoe Bay Bridge, Newport, OR	1996	Super- and substructure elements	5600 m^2	2 reference cells & 1 null probe per zone	2 years	NA
Upper Salt Creek Bridge, Redding, CA	1988	Deck	302 m^2	Potential wells	8 years	278

Note: Chloride ion content information was obtained from cores collected during this study.
NA - Not available
* parts per million

3.1.1. Yaquina Bay Bridge, Newport, Oregon

The historic Yaquina Bay Bridge was constructed in 1934 and carries northbound and southbound traffic over Yaquina Bay in Newport, Oregon.

3.1.1.1. Structure Information

The roadway is 8 meters wide and 994 m long. The substructure in each span comprises columns supported by two arches running parallel to the bridge, one on each side. The two ends of the arches are supported by footers at each pier. Diaphragm walls connect the two arches at a regular interval.

In 1989, a corrosion condition evaluation of the structure revealed that the bridge deck was in poor condition and required extensive rehabilitation. Thirteen hundred square meters of delaminated concrete were found. Corrosion-induced damage was also noted on the substructure elements.

3.1.1.2. CP Information

Arc-sprayed zinc was applied to various superstructure and substructure elements. These included the deck soffit, diaphragm, columns, arches, and piers. Prior to the installation of the CP system, areas of unsound and high-resistivity concrete were removed and repaired with pneumatically applied mortar. A very stringent quality-control plan was enforced during the rehabilitation. All elements of the structure to receive CP were enclosed and the environment inside the enclosure was controlled. Control of temperature and air quality was exercised to ensure good adhesion of arc-sprayed zinc to the concrete surface.

The system contains 58 zones, 55 of which are monitored and controlled by 8 rectifiers located on piers 4, 6, and 9. The first three zones have not been energized. Each of the 55 zones is instrumented with a graphite reference cell and a silver-silver chloride reference cell. Zones 4 and 8 have an additional graphite reference cell, and zones 10 and 14 have an additional silver-silver chloride reference cell. Twelve null probes, 6 each, were installed in zones 18 and 21. There is some confusion about the location of one set of these null probes. Although, the rectifier label states that the null probes are located in zone 16, the null probe wires are labeled zone 18 and the system ground of zone 18 is used for the measurement. For the purpose of this report, it is assumed that the probes are located in zone 18. System installation was completed in 1996.

The rectifiers are equipped with remote monitoring units (RMUs). These units provide system-operating parameter control and monitoring services, remotely or locally. As these rectifiers are not equipped with meters to directly read system-operating parameters, a portable computer must be connected to the RMUs during field evaluations.

3.1.1.3. Field Evaluations

Evaluations were performed on the following dates:

First evaluation	September 26 and 27, 1996	< 1 year old
Second evaluation	September 17 and 18, 1997	~ 1 year old
Third evaluation	October 26 to 28, 1998	~ 2 years old

3.1.1.4. Findings

System Component Evaluation

Electrical continuity between system grounds and reference cell grounds, and between reference cell grounds of the same zone were evaluated. The results of the DC continuity testing indicate significant lack of continuity, whereas more detailed analysis of AC continuity data suggests the presence of continuity. When the DC and the AC data are analyzed together, only a couple of discontinuities are observed out of the 400 measurements made in the three evaluations.

The impact of AC resistance on the performance of embedded reference cells has been a topic of significant discussion in the industry. *Task Force 29 Report - Guide Specifications for Cathodic Protection of Concrete Bridge Decks*[4], prepared by the American Association of State Highway & Transportation Officials-Association of General Contractors-American Road & Transportation Builders Association (AASHTO-AGC-ARTBA), requires that the AC resistance between reference cells and their grounds not exceed 10,000 ohms when embedded in concrete. As a significant number of reference cells were installed on this site, a summary of AC resistance data for these cells is provided in table 3-2.

Table 3-2. The AC Resistance Between Reference Cell and Reference Cell Ground

Reference Cell Type	No. of Measurements	AC Resistance (ohms)			
		Minimum	Maximum	Average	Standard Deviation
Graphite	115	320	32,000	4912	2736
Silver-silver chloride	115	740	76,000	9568	11,141

These data suggest that the average AC resistance was within the prescribed limits for proper reference cell operation. Of the 230 measurements, 7 for the graphite and 51 for the silver-silver chloride reference cell were in excess of 10,000 ohms. The impact of the higher resistance on the ability of the reference cells to perform reliably could not be determined from data collected in this study. In general, the resistance of the reference electrodes increased with time.

The current flow through the null probes was measured as a voltage drop across a 10-ohm resistor provided in the RMU. It should be noted that the null probe did not have a separate ground and the system ground was used for the purpose. During the first evaluation, zone 18 was not energized and thus only the null probes in zone 21 were evaluated. No null probes were tested in the second evaluation. The data for the null probes in zone 21 during the first evaluation shows the expected shift in current when the CP system is powered off. Many of the probes exhibited reversal of current flow, suggesting that the CP current was sufficient to shut off the macrocell current and provide a cathodic current to the probes. During the third evaluation, all null probes had the same reading and did not exhibit any change with the power off. The reason for this behavior was not determined.

The AC resistance between the anodes and the system grounds measured for each zone varied from 0.18 to 2.10 ohms, and averaged 0.49 ohms. These measurements are considered to be in the normal range.

Several zones during each trip were not powered up. It was learned that there was some problem in powering up the zones after a depolarization test had been remotely conducted using the RMUs.

System Performance

Visual and delamination surveys were conducted in certain sections of two zones during the first evaluation. A snooper was required and one lane of the bridge had to be shut down. The closing of the lane resulted in significant traffic backups and the research team was asked to avoid closing the lane in future evaluations. Thus, visual and delamination surveys were not performed during the second and third evaluations. A visual survey of the zinc surface indicated the formation of a white product. Analysis of the product by the Oregon Department of Transportation (DOT) indicated that it comprised zinc, chloride ions, and a small amount of sulfur. Some rust staining was observed in one area where no repairs were performed on cracks. No delaminations were noted in the areas tested.

The installation of the first 15 zones was not completed at the time of the first evaluation and thus these zones could not be evaluated. The first three zones were never energized. The remaining 12 zones were installed and energized by the second evaluation. One zone during the second evaluation and six zones during the third evaluation were observed to be powered off. It was later determined that some problems had been experienced in setting the output currents to these zones using the RMUs.

The true root mean square (TRMS) value of all rectifier output current and voltages was measured using an external multimeter. With a few exceptions, all zones were set to the same output current. During the first evaluation, the measured output current averaged 0.54 amps (A), with a standard deviation of 0.08 A. Similarly, during the second evaluation, the measured output current averaged 0.52 A, with a standard deviation of 0.02 A. During the third evaluation, 5 of the 55 zones were observed to be at a much higher current output than the remaining 50 zones. The measured output current for the remaining 50 zones averaged 1.00 A, with a standard deviation of 0.21 A. The output current for two of the five zones ranged from 10.00 to 11.00 A, and the other three zones were measured at 1.79 A. A summary of current densities is provided in table 3-3 below:

Table 3-3. The Current Density of Concrete Surface Area During Each Evaluation

Evaluation	No. of Measurements	Current Density (mA/m^2) of concrete surface area			
		Minimum	Maximum	Average	Standard Deviation
First	39	0.93	2.55	1.36	0.35
Second	54	0.90	1.82	1.23	0.24
Third	49	1.38	37.09	4.19	7.68

The average current densities presented in table 3-3 are significantly lower than the generally recommended range of 10.75 to 16.13 mA/m^2. The output voltages were in the acceptable range. The BEMF and the instant-off potentials were measured using the soft interrupt provided in the rectifier. A laptop computer was connected to the rectifier and a command was sent from the laptop computer to the rectifier for current interruption. Upon receipt of the command, the rectifier momentarily interrupted the output current. The peak-hold technique was used to measure the BEMF and the instant-off potentials. Prior to use of the peak-hold technique, a portable oscilloscope was used to verify the BEMF and instant-off measurements in the first few zones during the first trip.

Twenty of the 39 BEMF measurements made during the first trip were less than 500 millivolts (mV) and 4 of these were close to zero. A low BEMF can imply either insufficient CP current or a near short, and a zero BEMF can imply a short. Eleven of the 20 zones with the low BEMF measurements did not meet the 100-mV depolarization requirement in 24 hours. One of the zones exhibited negative depolarization. No BEMF measurements were made during the second evaluation. In the third evaluation, only two zones had BEMF less than 500 mV, one of which still did not meet the 100-mV depolarization criteria. It should be noted that the output current during the third evaluation was approximately double the output current during the first evaluation and may have resolved the low BEMF measurements for zones experiencing insufficient current during the first evaluation. Also, near shorts in an impressed-zinc system may be eliminated with time due to excessive consumption of zinc in that area. At least one zone is probably experiencing a near short or a short.

Depolarization data do not exhibit expected behavior. Only in 11 zones did depolarization measured by both reference electrodes exceed the 100-mV criterion and increase with an increase in current. In 18 zones, the average depolarization exceeded 100 mV, but one or more reference cell(s) exhibited a decrease in depolarization with an increase in current. There were 31 zones in which one or more reference cell(s) did not meet the 100-mV requirement in one or more trips. Either the current density was not sufficient and/or input/output (IO) measurements contained errors from spikes that were picked up during measurement.

3.1.1.5. Conclusions

All components of the system were functioning normally. The current outputs of most zones needed to be increased to obtain sufficient CP. If the system were continuously operated at these low current densities, then it would not be expected to provide complete protection and some corrosion-induced damage would be expected in the future.

3.1.2. Queen Isabella Causeway, South Padre Island, Texas

The Queen Isabella Causeway bridge structure on Park Road (PR) 100 links South Padre Island to the mainland of Texas at Port Isabel and spans the Laguna Madre.

3.1.2.1. Structure Information

The 4.0-km-long structure carries four lanes of traffic going east/west. It comprises 150 spans, 3 continuous steel plates, and 147 simple prestressed concrete girder spans. The spans are supported by 150 bents that are numbered from 1 to 150 from west to east. Construction of this structure was completed in 1973.

In 1997, a corrosion condition evaluation was conducted for the tie beams and footings located in bents 19 through 24. The footings exhibited cracks and spalls, the majority of which were located on the south footings. Spalls were mostly located on the sides of the footings. Cracking was the predominant mode of deterioration on the tie beams. The concrete cover depth ranged from 71 to 121 mm for the tie beams and from 58 and 108 mm for the footings. A corrosion potential survey of the members revealed a few areas where the potentials were more negative than -350 mV copper sulfate electrode (CSE). These areas were typically found in the proximity of cracks or construction joints.

3.1.2.2. CP Information

The tie beam and the three footings in bent 19 were protected with impressed-current arc-sprayed zinc. The entire surface of the tie beam and the footings was sprayed with zinc, with the exception of the bottom surface of the footings, covering approximately 127 m^2 of concrete surface area. The instrumentation consisted of three silver-silver chloride reference cells and two null probes. Two reference electrodes were embedded in the footings and one reference electrode was embedded in the tie beam. One null probe was installed in one of the footings and the other was installed in the tie beam.

Prior to the application of the anode, spalls and cracks were repaired and the concrete surface was sandblasted. The system was energized on October 7, 1997.

3.1.2.3. Field Evaluations

Data were collected during energization of the system and subsequently field evaluations were performed on the following dates:

Energization	October 7, 1997	
First evaluation	December 17 and 18, 1997	2 months old
Second evaluation	February 9 to 11, 1998	4 months old
Third evaluation	April 1 to 3, 1998	6 months old
Fourth evaluation	June 3 to 6, 1998	8 months old
Fifth evaluation	November 9 to 12, 1998	13 months old

The energization of the system was performed by the contractor.

3.1.2.4. Findings

System Component Evaluation

Data collected during energization indicate that all system components were responding well, with the exception of reference cell 1. The other two reference cells exhibited increased polarization with an increase in output current, and the null probes also experienced an increase in current flow with an increase in output current. The flow of current reversed in the null probes as the cathodic current was applied.

Electrical continuity testing was performed at the rectifier using DC and AC techniques. Continuity testing was performed during the depolarization test when the power to the system was off. It was performed between the grounds of reference electrodes in each zone and between the grounds of reference electrodes and the system ground of the subject zone. It should be noted that all measurements were made at the rectifier, which was installed at one end of the bridge. The bent was located at a significant distance from the end of the bridge and the lengths of the wires connecting the zone to the rectifier were in excess of a quarter of a mile.

The reference cell ground of reference cell 1 was found to be discontinuous and the reference cell was observed to be unstable in all five evaluations. The null probes performed well and often exhibited reversal in current flow when the cathodic current was terminated and/or exhibited reduction in current flow when the system was powered down.

Accurate measurement of instant-off potential was made difficult by the presence of electrical noise or current flow in the system. The peak-hold method could not be used to collect instant-off data. Manual interrupt had to be used. Even during manual interrupt, an external electrical signal could be observed on the oscilloscope. In two out of the five evaluations, accurate instant-off potentials could not be obtained.

The AC resistance between the reference electrodes and the reference cell grounds for all three electrodes in all five evaluations was equal to or less than 10,000 ohms. The AC resistance between the anode and the system ground averaged 5.16 ohms.

System Performance

On bent 19, which was protected with impressed-current zinc, an approximately 0.1-m-wide band of whitish products was observed at the bottom of the side faces of the footings. This band of whitish products indicates accelerated consumption of the sprayed zinc coating at the location.

The rectifier output voltage and BEMF were observed to be in the acceptable range, and the average concrete current density for the three field evaluations ranged from 11.65 to 24.57 mA/m^2. The average was 15.15 mA/m^2. Polarization decay for all operating embedded reference cells averaged 152 mV in 4 hours.

3.1.2.5. Conclusions

With the exception of one reference electrode, all other system components were performing adequately. Depolarization test results exceeded the 100-mV criterion for the two operating reference cells. The null probes indicated that the current supplied by the CP system was adequate to overcome the corrosion current in the protected area. The band of whitish products at the bottom of the side faces of the footers suggested that at high tide when this section of the footers was submerged, current leaked from the anode to the bay water. Such current leaks result in accelerated consumption of the anode in the affected areas.

3.1.3. Depoe Bay Bridge, Newport, Oregon

The Depoe Bay Bridge carries northbound and southbound traffic of Pacific Highway 101 over Depoe Bay in Newport, Oregon.

3.1.3.1. Structure Information

The arch bridge was built in 1926 and was widened in 1939. The bridge has four lanes, with a total length of 99 m and a 15.2-m-wide roadway.

3.1.3.2. CP Information

In 1996, arc-sprayed zinc was installed on the sidewalk soffit, sidewalk brackets and beams, deck soffit, longitudinal deck girders, transverse deck beams, arch ribs, struts, and columns of the Depoe Bay Bridge. Three rectifiers control 14 zones for a total protected area of 6032 m^2. Sprayed zinc was applied in zones 1 through 13, for an approximate total zinc-protected area of 5600 m^2.

Zones 1 through 13 are instrumented with a graphite reference cell and a silver-silver chloride reference cell. Every zone is instrumented with a null probe.

Delaminated concrete was removed and repairs were performed using shotcrete before the CP system was installed.

3.1.3.3. Field Evaluations

Evaluations were performed on the following dates:

First evaluation	September 28 and 29, 1996	< 1 year old
Second evaluation	September 19 and 20, 1997	~ 1 years old
Third evaluation	October 27 and 28, 1998	~ 2 years old

3.1.3.4. Findings

System Component Evaluation

Three field evaluations have been conducted on this system. The last evaluation was conducted after the system had been in service for about 2 years. At the time of the first evaluation, the arc-sprayed zinc had been shorted to the reinforcing steel and was functioning sacrificially because the rectifiers had not been installed. The rectifiers were found to have been installed during the second evaluation, but some measurements could not be obtained for cabinet 1 since it was not accessible. During the third evaluation, the zones controlled by cabinets 1 and 2, with the exception of zone 1, were found to be de-energized.

Electrical continuity testing of the reference cell grounds to the system grounds and of the reference cell grounds to the reference cell grounds indicated that the reference cell grounds of both cells in zone 3 and the silver-silver chloride reference cell in zone 13 were discontinuous.

In general, the AC resistance between the reference cell and its ground for the silver-silver chloride reference cells were found to be much higher than the graphite reference cells. The AC resistance between the silver-silver chloride reference cell of zone 4 and its ground was 92,000 ohms. The AC resistance for the graphite reference electrodes averaged 2873 ohms and the silver-silver chlorides averaged 19,337 ohms, excluding the one measuring 92,000 ohms.

During the second evaluation, null probe measurements could only be taken from cabinet 2, which controls zones 6 through 10. The null probe currents either reversed or went to zero upon de-energization. Similar behavior was noted for zones 11 through 13 during the third evaluation. The current flowing through the null probes for the zones in cabinet 2 during the third evaluation was positive when the system's power was off. The currents decreased when the system was powered up, but did not reverse, indicating that the cathodic current was not sufficient to overcome corrosion currents.

Information from Oregon DOT indicated that some problems were being experienced in setting operating parameters using the RMUs. These monitoring units were similar to the ones at Yaquina Bay Bridge.

System Performance

The output voltage and BEMF measurements were in the acceptable range. The anode to system ground AC resistance averaged 0.42 ohms during the first evaluation and 0.52 ohms during the third evaluation.

The average current density for the operating zones was 1.21 mA/m^2 during the second evaluation and 1.46 mA/m^2 during the third evaluation. The average depolarization for zones 5, 6, and 11 did not exceed 100 mV; all other zones exceeded 100 mV during the second evaluation. During the third evaluation, depolarization did not exceed 100 mV in three of the four operational zones.

3.1.3.5. Conclusions

With the exception of two discontinuities, all other components of the system were operational. Due to problems with the RMUs in setting the output parameters, the system was not operating continuously and was not providing protection as would be desired. Also, the operating current densities were not sufficient to overcome the ongoing corrosion in the bridge elements.

3.2. Zinc Strip

3.2.1. Upper Salt Creek Bridge on Southbound I-5, Redding, California

The Upper Salt Creek Bridge carries southbound I-5 in Redding, California.

3.2.1.1. Structure Information

The bridge is 11.4 m long and 3.6 m wide, with a deck surface area of 446 m^2. Construction of the Upper Salt Creek Bridge was completed in 1966.

3.2.1.2. CP Information

A metallized zinc CP system was installed on the southern half of the bridge deck (zone 1) on a total surface area of 223 m^2 in 1998.

The metallized zinc system comprises a grid of 150-mm-wide and 0.61-mm-thick arc-sprayed zinc strips at 300 mm on center. The zinc strips were sprayed on the prepared concrete deck surface. The power connection to the zinc strips was achieved with brass pads installed flush with the concrete surface and in contact with the arc-sprayed zinc strips. A 110-mm-thick asphalt concrete overlay was then placed on the deck.

There were no embedded reference cells or rebar probes installed in the system. However, potential wells were installed on the bridge deck to facilitate potential measurements using an external reference electrode. A constant voltage rectifier was used to power the system.

3.2.1.3. Field Evaluations

Evaluations were performed on the following dates:

First evaluation	October 31 to November 4, 1994	~ 6 years old
Second evaluation	November 26 and 27, 1996	~ 8 years old

3.2.1.4. Findings

System Component Evaluation

No instrumentation was installed in this system. A visual survey of the potential wells indicated that water was collecting under the asphalt overlay and shorting the potential wells with the zinc anode. Thus, the wells could not be used to measure potential of the embedded steel.

During the second evaluation, the system was found to be powered off. The power to the system was turned on and rectifier data were collected.

System Performance

The concrete current density during the first evaluation was 2.2 mA/m^2 and the output voltage and BEMF were in the acceptable range.

3.2.1.5. Conclusions

The performance of this system could not be judged based on the data available. The concept of installing potential wells was a good one, but the wells were not isolated properly from the anode.

4.0. TITANIUM-BASED IMPRESSED-CURRENT CP SYSTEMS

4.1. Titanium Mesh Anode

Five CP systems installed on highway structures using titanium mesh as an auxiliary anode were included in this study. Three of the systems were installed on bridge decks, one on the underside of a roadway in a tunnel and one on bridge substructure elements. Table 4-1 lists pertinent information on these five CP systems:

Table 4-1. Titanium Mesh Impressed-current CP Systems

Structure Name and Location	Year CP System Installed	Element Protected	Area Protected	Instrumentation	Age at Last Evaluation	Average Chloride Ion Content of Steel Depth (ppm)
Wawecus Hill Road Bridge, Norwich, CT	1992	Deck	1124 m^2	1 reference cell & 1 null probe per zone	7 years	875
Brooklyn Battery Tunnel, New York, NY	1992	Underside of roadway slab	10332 m^2	4 reference cells per zone	6 years	4170 top mat 515 bottom mat
Columbia Road Bridge, Westlake, OH	1986	Deck	985 m^2	3 reference cells & 4 current probes	12 years	NA
6th Street Bridge, Sioux Falls, SD	1991	Deck	1515 m^2	1 reference cell per zone	6 years	239
Queen Isabella Causeway, South Padre Island, TX	1997	Tie beam & footings in bent	127 m^2	3 reference cells & 1 null probe	13 months	1132 in the footing

NA - not available.
Note: Chloride ion content information was obtained from cores collected during the study.

4.1.1. Wawecus Hill Road Bridge Over I-395, Norwich, Connecticut

The Wawecus Hill Road Bridge carries eastbound and westbound traffic over I-395 in Norwich, Connecticut.

4.1.1.1. Structure Information

The bridge comprises four simple spans, with a total length of 92.8 m. The bridge has a skew angle of approximately 57 degrees and a total width of 13.9 m (two 6-m-wide travel lanes and two 0.86-m-wide sidewalks). Construction of the bridge was completed in 1958. In August

1990, a condition evaluation of the structure revealed that the bridge deck was in poor condition and required extensive rehabilitation.

4.1.1.2. CP Information

Deteriorated concrete was removed by hydro-demolition and a monolithic low-slump dense concrete pour was used to patch the deteriorated areas and place an overlay. The thickness of the concrete placement varied from 40 mm to full depth. The titanium mesh anode was placed between the hydro-demolished surface and the overlay. A plastic spacer mesh was used to isolate the titanium mesh from the reinforcing steel exposed by hydro-demolition.

The CP system was subdivided into four individual zones, each zone had one span. A total deck surface area of 1124 m^2 was protected by the CP system. In sections of the deck where additional steel was required, epoxy-coated rebars were used. The epoxy-coated rebars were made continuous to the black steel. Each zone was instrumented with two silver-silver chloride reference cells and two null probes. The system was installed and energized in 1992.

4.1.1.3. Field Evaluations

Evaluations were performed on the following dates:

First evaluation	July 6 and 7, 1995	~ 3 years old
Second evaluation	June 18, 1997	~ 5 years old
Third evaluation	July 29 and 30, 1999	~ 7 years old

4.1.1.4. Findings

System Component Evaluation

The DC electrical continuity test data for each evaluation exhibited discontinuity. Electrical continuity data obtained during the last two evaluations using the AC and the half-cell potential method suggest the presence of electrical continuity.

The AC resistance measurement between the reference cells and their respective grounds indicated that one reference cell in zone 1 had AC resistance in excess of 100,000 ohms throughout the study, and the resistance of the other reference cell in the same zone increased with time to similar levels. Such high resistances can cause an error in potential measurement due to pickup of electrical noise. The AC resistances for the remainder of the reference cells were within the AASHTO-prescribed limits, with the exception of one reference cell in zone 4 and one in zone 3, which exhibited resistances in excess of 10,000 ohms at times.

Three of the eight null probes were not functional. One had a broken wire and two others had shorts. The remaining null probes exhibited reversal of current flow when the system was powered down.

The readings taken from the rectifier meters were in good agreement with the external meter used to validate them.

System Performance

No corrosion-induced deterioration was observed on the top or bottom surfaces of the deck. Hollow-sounding areas were detected over less than 0.1 percent of the top deck surface. It is suspected that the hollow-sounding areas resulted from disbondment of the overlay.

The average concrete current density for the three evaluations ranged from 8.61 to 12.06 mA/m^2. With the exception of zone 1, all other zones were running at a current density lower than the generally recommended 10.75 mA/m^2. The anode-to-steel AC resistance averaged 0.66 ohms for all zones and the output voltage and BEMF were in the acceptable range.

In general, the 100-mV polarization decay criterion was met for all zones. Some fluctuations in polarization decay for zones 1 and 3 were noted. Reference cell 2 in zones 1 and 3 did not meet the 100-mV criterion in two of the three evaluations. Depolarization measurements made with external reference cells in potential wells also exceeded 100 mV. The null probe data suggest that the system is putting out sufficient current to reverse the macrocell in areas where the null probes are located.

4.1.1.5. Conclusions

With the exception of the three null probes, all other components were functioning properly. The system was providing adequate protection for the reinforcement.

4.1.2. Brooklyn Battery Tunnel, New York, New York

The Brooklyn Battery Tunnel, built beginning in 1940 and completed in 1950, connects Battery Park in lower Manhattan with the Red Hook section of Brooklyn.

4.1.2.1. Structure Information

The Brooklyn Battery Tunnel consists of two parallel tubes that are 2780 m long between the entrance and exit portals. Each tube is 9.5 m in diameter and is subdivided into three conduits by a roadway slab and a ceiling slab. The lower conduit serves as a fresh air duct, the middle conduit serves as the roadway, and the upper conduit serves as the exhaust duct. The roadway slab is 6.1 m wide and 360 mm thick. The top surface of the roadway slab is covered by 100 mm of asphalt pavement.

In 1990, a condition survey revealed that the roadway slab was in poor condition. Spalled concrete exposing severely corroded rebars was observed.

4.1.2.2. CP Information

Following a 1990 condition survey of the roadway slab, deteriorated asphalt on the top surface and concrete on the top and bottom surfaces were repaired. All delaminated and unsound concrete from the roadway slab was removed. At some locations, reinforcing steel bars on the bottom mat of the steel experiencing significant loss of cross section were removed and replaced with epoxy-coated rebar. The epoxy-coated rebar was tied to the existing steel reinforcement by welding.

In 1992, a titanium mesh anode was installed on select rehabilitated sections of the soffit of the roadway slab. A total of 10,332 m^2 of concrete surface area was protected by the CP system. The titanium mesh anode was secured to the concrete surface with plastic fasteners and encapsulated in a shotcrete overlay. There were problems with the development of the bond between the shotcrete and the original concrete. Several unsuccessful attempts were made to improve the bond. As a last resort, it was decided that plastic pins would be installed to hold the overlay in place. The CP system comprises 42 zones that are controlled by 14 rectifiers (7 rectifiers in each tube). Each rectifier is equipped with an RMU. Each zone is instrumented with an embedded graphite reference cell and a current probe.

4.1.2.3. Field Evaluations

Evaluations were performed on the following dates:

First evaluation	July 17 and 18, 1995	~ 3 years old
Second evaluation	June 9 and 10, 1997	~ 5 years old
Third evaluation	September 23 to 25, 1998	~ 6 years old

4.1.2.4. Findings

System Component Evaluation

Three field evaluations have been conducted on this system. The last evaluation was conducted after the system had been in service for about 6 years. At the time of the first evaluation, a contractor was attempting to restore the mechanical bond of the disbonded overlay by anchoring it to the original concrete surface with plastic fasteners. The sections of the soffit of the roadway slab, which were not rehabilitated, were found to be in poor condition and widespread spalling with exposed and corroded rebar was visible.

Access to the rectifiers was restricted due to other ongoing rehabilitation work in the tunnel. In the first, second, and the third evaluations, access was available to three, six, and nine rectifiers, respectively.

The anode-to-system ground data indicated that there were no electrical shorts between the anodes and the system grounds. In the rectifiers evaluated, generally no continuity was detected between system grounds and between reference cell grounds and their respective system ground using the DC method, whereas, AC measurements suggested the presence of continuity. The DC continuity data suggest that currents from some source are flowing in the roadway slab. Considering the amount of corrosion damage that is observed in the area not yet rehabilitated, it is suspected that corrosion in areas not receiving sufficient current is ongoing.

System Performance

The significant lack of bonding between the overlay and the roadway slab, the localized presence of moisture in the roadway slab, and the possibility of freeze-thaw damage render the CP system inefficient, ineffective, and/or non-functional. Lack of bonding impairs the efficient and effective current distribution to all steel to be protected in the roadway. Current flow from the anode to the steel occurs only in areas with sufficient bond. If moisture from the roadway slab finds its way between the overlay and the roadway slab, it could enhance current distribution locally. However, unless the overlay were watertight, it would be difficult for water to completely fill the cavity produced by the disbondment, as the tunnels are inclined. Thus, the CP system is providing protection only in areas of good bonding and in isolated areas where moisture has completely filled the cavities caused by disbondment. It is believed that moisture is not present everywhere or all the time.

Measurement of rectifier output parameters indicates that a CP current is being impressed to each zone. The average current density for each evaluation varied from 29.60 to 34.33 mA/m^2 of concrete surface area. The current densities impressed on the system are significantly higher than normally encountered for corrosion mitigation. The output voltage and BEMF are in the acceptable range except for one zone (the output voltage, current, and BEMF for this zone indicate that a short or a near short is present). The average anode-to-system ground resistance was 0.30 ohms.

The results of the depolarization testing for all evaluations can be summarized as follows:

Table 4-2. Results of Depolarization Testing (in percent)

	First Evaluation	Second Evaluation	Third Evaluation
> 100 mV	9	11	15
0 to 100 mV	73	11	73
Negative Depolarization	18	78	12

Depolarization test results indicate that the distribution of CP current varies as a function of environmental conditions, especially the presence of moisture between the overlay and the original concrete.

4.1.2.5. Conclusions

Considering the higher level of current densities being impressed on the roadway slab, the results of the depolarization testing, and the DC continuity data, it was clear that the system was not performing efficiently and effectively. The primary reason for the lack of performance was improper installation of the system. One cannot expect a CP system to perform when the majority of the overlay is disbonded.

4.1.3. Columbia Road Bridge, Westlake, Ohio

The Columbia Road Bridge is located on Columbia Road over I-90 in Westlake, Ohio.

4.1.3.1. Structure Information

The bridge has four spans, with a total length of 83 m and a roadway width of 24 m. The total deck area is approximately 1970 m^2. The substructure consists of two reinforced concrete piers and two reinforced concrete abutments. Construction of the Columbia Road Bridge was completed in 1974.

Before the CP system was installed, the deck had delaminations over 1 percent of its surface area and the average chloride ion content at the steel depth was 178 ppm.

4.1.3.2. CP Information

In 1986, a CP system utilizing a titanium mesh anode was installed on the two southbound lanes. The southbound lanes were divided into two independent zones, each 83 m long and 6 m wide. The deck was overlaid with 64 mm of superplasticized dense concrete. The anode was not installed on the northbound lanes. These areas were overlaid, however, and were designated as the controls. Each zone was instrumented with two silver-silver chloride reference cells, two rebar probes, and two Corrosometer® probes.

4.1.3.3. Field Evaluations

Evaluations were performed on the following dates:

First evaluation	September 8 and 9, 1994	~ 8 years old
Second evaluation	March 25, 1997	~ 11 years old
Third evaluation	April 22 and 23, 1998	~ 12 years old

4.1.3.4. Findings

System Component Evaluation

Electrical continuity data reflected good continuity of system grounds to reference cell grounds and system grounds to system grounds. The AC resistance data for one reference cell during the first evaluation was close to 100,000 ohms and two others exceeded 10,000 ohms. The AC resistance for these three reference electrodes increased to above 100,000 ohms during the second evaluation and remained at very high levels. Two of these three exceeded 500,000 ohms during the second evaluation.

The corrosion probes were observed to be functioning as intended with the exception of one that was missing a resistor since the first evaluation and another probe that exhibited a broken wire during the third evaluation.

System Performance

The output voltage and BEMF values were in the acceptable range and the average anode-to-system ground resistances varied from 0.30 to 0.34 ohms.

No corrosion-induced deterioration of the deck surface of the protected area and the control area was observed during the first evaluation. Only non-corrosion-induced spalls were observed in the protected area during the first evaluation. Evaluations before the start of this study had noted some bond failure between the overlay and the original deck concrete. However, corrosion-induced spalls were found on the deck soffit and, in general, the soffit of the protected area exhibited more spalling than the control area during all evaluations. During the third evaluation, delamination on the deck surface measuring 0.09 m^2 in the protected area and 0.45 m^2 in the control area was observed. It is not known whether these delaminations were corrosion-induced. Rust stains were visible on the unprotected sidewalks and the median.

The average concrete current density varied from 8.04 to 13.08 mA/m^2 during the three evaluations. Every reference cell tested met the 100-mV criterion during each evaluation. All corrosion probes tested exhibited reversal of current with system power up and power down. The corrosion probes installed in the control area exhibited high macrocell current, indicating ongoing corrosion in the control area.

4.1.3.5. Conclusions

All components of the system were functioning properly and the system was providing adequate protection to the top mat steel. There were indications that corrosion was ongoing in the unprotected section of the deck, and this section may experience corrosion-induced damage in the future. The corrosion-induced damage on the soffit of the protected area was of concern. It was not known whether this damage existed at the time of the installation of the system and has remained constant, or whether it has increased with time while the deck was cathodically protected. In this study, sufficiently detailed information was not collected on the soffit damage to ascertain whether it increased with time.

4.1.4. Bridge over Big Sioux River, Sioux Falls, South Dakota

The Sixth Street Bridge is a four-lane structure over the Big Sioux River in Sioux Falls, Minnehaha County, South Dakota.

4.1.4.1. Structure Information

The bridge has a total length of 71 m and a roadway width of 15 m. Construction of the bridge was completed in 1975.

A condition evaluation of the bridge revealed that more than 10 percent of the deck surface area was delaminated and the average chloride ion content at the steel depth exceeded 2600 ppm.

4.1.4.2. CP Information

In 1991, a CP system utilizing a titanium mesh anode was installed on the deck, the two sidewalks, and the curb barriers that separate the sidewalks from the deck. The CP system was installed to control corrosion on 1515 m^2 of concrete surface area. This area was divided into six zones with zones 1 through 4 located on the deck and zones 5 and 6 on the sidewalks and curb barriers. Each zone was instrumented with a silver-silver chloride reference cell. The deck was overlaid with 64 mm of low-slump dense concrete, and a thin overlay of pre-bagged fast-setting material was installed on the curb and the curb barriers.

Before the CP system was installed, delaminated concrete was removed, and repairs were performed using A45 Class concrete.

4.1.4.3. Field Evaluations

Evaluations were performed on the following dates:

First evaluation	September 16 and 17, 1994	~ 2 years old
Second evaluation	July 29 to August 1, 1996	~ 4 years old
Third evaluation	May 15 and 16, 1998	~ 6 years old

4.1.4.4. Findings

System Component Evaluation

Electrical continuity testing, AC resistance measurements, and unstable potentials identified one bad reference cell ground and one non-functional reference electrode. The reference cell ground was corrected by shorting to another ground. All other components of the system were observed to be performing normally.

System Performance

The system output voltage, BEMF, and anodes-to-system ground resistances were found to be in the acceptable range. The average anode-to-system ground resistance varied from 0.53 to 0.65 ohms.

Before installation of the CP system, the chloride ion content in the concrete at the steel depth was several times higher than the threshold required to initiate corrosion. During the 4-year span of the evaluations, the system has been operating at current densities ranging from 8.93 to 9.90 mA/m^2. At these current densities, all embedded reference cells (except one that was not operational) met the 100-mV depolarization criterion. The reference electrode in zone 5 exhibited a depolarization value of 372 mV in the first evaluation and depolarization values in excess of 400 mV in the remaining two evaluations. Such high depolarization is of concern, especially at a current density of less than 10 mA/m^2.

At the time of the last field evaluation, a few longitudinal cracks were observed on the overlay surface and minor cracking was evident on the sidewalks and deck underside. Hollow-sounding areas were detected in all evaluations in zone 5. System installation reports indicate that disbondment of the thin overlay installed on the sidewalks has been a problem from the time of the system installation. In conjunction with the high polarization values for zone 5, this suggests that disbondment of the overlay is concentrating the current in that zone to sections with good bond, hence the high depolarization values.

4.1.4.5. Conclusions

All system components, with the exception of one reference electrode, were functioning normally and the system was providing adequate protection. The disbondment of the thin overlay was of concern. If the amount of area disbonded increases with time, the effectiveness of the CP system will be reduced in the subject zone.

4.1.5. Queen Isabella Causeway, South Padre Island, Texas

The Queen Isabella Causeway is a 4.0-km-long bridge structure on PR 100 that links South Padre Island to the mainland of Texas at Port Isabel and spans the Laguna Madre.

4.1.5.1. Structure Information

The causeway carries four lanes of traffic going east/west. It comprises 150 spans, 3 continuous steel plates, and 147 simple prestressed concrete girder spans. The spans are supported by 150 bents that are numbered from 1 to 150 from west to east. Construction of this structure was completed in 1973.

In 1997, a corrosion condition evaluation was conducted for the tie beams and footings located in bents 19 through 24. The footings exhibited cracks and spalls, the majority of which were located on south footings. Spalls were mostly located on the sides of the footings. Cracking was the predominant mode of deterioration on the tie beams. The concrete cover depth ranged from 71 to 121 mm for the tie beams and from 58 and 108 mm for the footings. A corrosion potential survey of the members revealed a few areas where the potentials were more negative than -350 mV CSE. These areas were typically found in the proximity of cracks or construction joints.

4.1.5.2. CP Information

The tie beam and the three footings in bent 21 were protected with a titanium mesh anode. The titanium mesh anode was installed on the entire surface of the tie beam and the footings with the exception of the bottom surface of the footings. The titanium mesh anode was encapsulated in a cementitious overlay. The total surface area covered with the titanium mesh was approximately 127 m^2. The instrumentation consisted of three silver-silver chloride reference cells and two null probes. Two reference electrodes were embedded in the footings and one reference electrode was embedded in the tie beam. One null probe was installed in one of the footings and the other in the tie beam.

Spalls and cracks were repaired and the concrete surface was sandblasted prior to the application of the anode. The installation of the concrete overlay encapsulating the titanium mesh was done three times. The first two times the overlay was installed, the overlay and the mesh had to be removed. The first application involved trowel-applied Sikatop® 123. This product is intended for patch repair rather than overlay application. Two days after the application of the system, the overlay exhibited very severe cracking and was removed. The second application involved trowel-applied Emaco® S88-CA manufactured by Master Builders. Two days after the application of the overlay, hammer sounding was conducted to test for delaminations. Delaminated areas amounted to 25 percent of the concrete overlay. Seven days later, the delaminated areas had increased to 75 percent and were prevalent in the vertical and overhead orientations. The overlay was again removed. The main reason for the failure of the second trial was inadequate surface preparation. The surface preparation for the third trial included scabbling with hand-held milling machines in addition to sandblasting. The concrete overlay was dry-mix shotcrete applied for the third and final application of the overlay.

4.1.5.3. Field Evaluations

CONCORR, Inc. personnel were present during the initial energization of the system; subsequent evaluations were performed on the following dates:

Energization	October 7, 1997	
First evaluation	December 17 and 18, 1997	~ 2 months old
Second evaluation	February 9 to 11, 1998	~ 4 months old
Third evaluation	April 1 to 3, 1998	~ 6 months old

Fourth evaluation	June 3 to 6, 1998	~ 8 months old
Fifth evaluation	November 9 to 12, 1998	~ 13 months old

4.1.5.4. Findings

System Component Evaluation

During energization of the system, all components, with the exception of the RMU, were functioning properly. By the time of the second evaluation, the RMU problem had been rectified. The DC electrical continuity data erroneously indicated that there was a lack of continuity. This was attributed to the flow of corrosion currents in the reinforcing steel when the system was off. During the second evaluation, a 0.14- m^2 hollow-sound area was identified. The hollow sound in this area was attributed to disbondment of the encapsulation.

System Performance

The average concrete current density for the three field evaluations ranged from 12.37 to 22.93 mA/m^2. Polarization decay for all embedded reference cells was in excess of 100 mV and averaged 255 mV for all evaluations in 4 hours. The null probes exhibited a reduction in current to zero or reversal upon system power off. The output voltages and BEMF measurements were in the acceptable range. The AC resistance between the anode and the system ground averaged 4.5 ohms.

4.2. Titanium Ribbon Anode

Only one structure with a titanium ribbon anode installed as an auxiliary anode was included in this study. Pertinent information is provided in table 4-3:

Table 4-3. Titanium Ribbon Impressed-current CP Systems

Structure Name and Location	Year CP System Installed	Element Protected	Area Protected	Instrumentation	Age at Last Evaluation	Average Chloride Ion Content of Steel Depth (ppm)
Rte. 229 Bridge, Southington, CT	1989	Deck	2057 m^2	1 Reference Cell per zone	9 years	1103

Note: Choride ion content information was obtained from cores collected during this study.

4.2.1. Route 229 Bridge Over I-84, Southington, Connecticut

The bridge on Route 229 over I-84 (bridge number 1242) in Southington, Connecticut, was constructed in 1960.

4.2.1.1. Structure Information

The bridge has five spans, with a total length of 125 m and a curb-to-curb roadway width of 16.5 m. The bridge consists of four lanes (two northbound and two southbound) and a 1.5-m-wide sidewalk on each side.

In 1986, a comprehensive condition evaluation of the bridge deck was conducted. Visual and delamination survey results indicated that 10 percent of the deck surface area was patched, spalled, or delaminated. The chloride ion content at the steel depth varied from 199 ppm to 3100 ppm and approximately 90 percent of the area surveyed using the half-cell potential technique exhibited active potentials (i.e., potentials more negative than -350 mV).

4.2.1.2. CP Information

During the summer and fall of 1989, an impressed-current CP system utilizing 6.4-mm-wide titanium ribbon as the anode material was installed. The anode ribbon was placed below the top mat epoxy-coated reinforcing steel at a spacing of 305 mm on center. The CP system was powered by a single 10-circuit rectifier and protected 2057 m^2 of concrete surface divided into 10 zones. Each of the 10 zones was instrumented with one silver-silver chloride reference cell. All reference cells were cast-in-concrete cubes and these cubes were placed adjacent to the epoxy-coated rebar. Design drawings specified chloride-contaminated concrete for the manufacture of these cubes. System grounds were installed on the top epoxy-coated reinforcing steel mat. Bond cables between the top mat of reinforcing steel and the bottom mat of reinforcing steel were installed to ensure continuity between the two mats.

Zones 1 through 5 have one common header wire and the ground for zone 6 was found to be discontinuous soon after installation of the system. To resolve this problem, all system grounds were shorted.

As part of the rehabilitation project, the concrete below the top mat reinforcement was removed, the top mat of steel was replaced with epoxy-coated rebar, and the bridge deck was resurfaced with a monolithic concrete pour. With the exception of some locations where full-depth (184-mm-deep) repairs were required, the depth of the concrete repairs averaged 114 mm.

4.2.1.3. Field Evaluations

Evaluations were performed on the following dates:

First evaluation	July 10 and 11, 1995	~ 6 years old
Second evaluation	June 17 and 18, 1997	~ 8 years old
Third evaluation	June 27, 1998	~ 9 years old

4.2.1.4. Findings

System Component Evaluation

The AC, DC, and potential continuity test data do not show a clear pattern of continuity. The AC resistance measurements in some cases exceeded 50 ohms and, in many cases, exceeded 10 ohms. The level of discontinuity detected in this system was higher than normally encountered. The potentials measured by the reference cells did not indicate any lack of electrical continuity and exhibited correct movement of the steel potential with the change in the system current. The use of epoxy-coated rebars in the top mat probably complicated the detection of and the presence of continuity. All reference cells were functioning as expected. The AC resistances between the reference cells and their respective grounds were less than 10,000 ohms for all of the evaluations.

System Performance

Three field evaluations were conducted and the system was in its ninth year of service at the time of the most recent evaluation. A small amount of delamination was detected during the first and the last evaluations. Cores were collected from the delaminated areas and it was determined that the delaminations were a result of failure of the bond between the overlay and the original concrete.

The 100-mV polarization criterion was satisfied in 4 hours at all locations in all evaluations except for zone 7 during the third evaluation. The stability of this reference cell was suspect. The system was operating at an average current density ranging from 2.9 to 3.3 mA/m^2 from one evaluation to another.

4.2.1.5. Conclusions

With the exception of one reference cell, all other system components were functioning normally. The presence of epoxy-coated rebar in the top mat was making it difficult to interpret continuity data using DC, AC, and half-cell techniques.

4.3. Arc-sprayed Titanium

Two experimental installations of arc-sprayed titanium anode were included in this study. Both systems were installed in only one of the zones in each of the two bridges. Pertinent information on each system is provided in table 4-4:

Table 4-4. Arc-Sprayed Titanium Impressed-current CP Systems

Structure Name and Location	Year CP System Installed	Element Protected	Area Protected	Instrumentation	Age at Last Evaluation	Average Chloride Ion Content of Steel Depth (ppm)
Depoe Bay Bridge, Newport, OR	1996	Super- & Substructure Elements	6032 m^2	3 reference cells & 1 null probe	2 years	NA
Queen Isabella Causeway, South Padre Island, TX	1997	Tie beam & footings in bent	127 m^2	3 reference cells & 1 null probe	13 months	598 in the footing

NA - not available.
Note: Chloride ion content information was obtained from cores collected during the study.

4.3.1. Depoe Bay Bridge, Newport, Oregon

The Depoe Bay Bridge carries the northbound and southbound traffic of Pacific Highway 101 over Depoe Bay in Newport, Oregon.

4.3.1.1. Structure Information

This arched bridge was built in 1926 and was widened in 1939. The bridge has four lanes, with a total length of 99 m and a 15.2-m-wide roadway.

4.3.1.2. CP Information

In 1996, arc-sprayed titanium was installed on the sidewalk soffit, sidewalk brackets and beams, deck soffit, longitudinal deck girders, and transverse deck beams of the Depoe Bay Bridge. Arc-sprayed titanium zinc was applied only in one zone (zone 14) to protect 451 m^2. Arc-sprayed zinc was applied in zones 1 through 13.

Zone 14 was instrumented with two graphite reference electrodes, a silver-silver chloride reference electrode, and a null probe. Delaminated concrete was removed and repairs were performed using shotcrete before the CP system was installed.

4.3.1.3. Field Evaluations

Evaluations were performed on the following dates:

First evaluation	September 28 and 29, 1996	0 years old
Second evaluation	September 19 and 20, 1997	< 1 year old
Third evaluation	October 27 and 28, 1998	> 1 year old

4.3.1.4. Findings

System Component Evaluation

Three field evaluations have been conducted on this system. The last evaluation was conducted after the system had been in service for about 2 years. At the time of the first evaluation, the rectifier installation had not been completed and the arc-sprayed titanium system was not operational. It was determined during the second evaluation that the rectifiers had been installed.

Electrical continuity testing of the reference cell grounds to the system grounds and the reference cell grounds to the reference cell grounds indicated that the expected continuity was present. The AC resistance between the anode and the system grounds was found to be in the reasonable range. The AC resistance between the reference cells and their respective grounds averaged 1500 ohms for the graphite and 19,000 ohms for the silver-silver chloride reference electrode.

System Performance

Null probe currents went to zero when the system was powered off. All reference cells met the 100-mV criterion during each evaluation, and the system was operating at an average current density of 1.0 mA/m^2. The system had not been operated continuously due to problems experienced in setting the output parameters via the RMU.

4.3.1.5. Conclusions

All system components were functioning properly. The effectiveness of the system was being compromised due to interruption of the operation of the system.

4.3.2. Queen Isabella Causeway, South Padre Island, Texas

The Queen Isabella Causeway is a 4.0-km long bridge structure on PR 100 that links South Padre Island to the mainland of Texas at Port Isabel and spans the Laguna Madre.

4.3.2.1. Structure Information

The structure carries four lanes of traffic going east/west. It comprises 150 spans, 3 continuous steel plates, and 147 simple prestressed concrete girder spans. The spans are supported by 150 bents that are numbered from 1 to 150 from west to east. Construction of this structure was completed in 1973.

In 1997, a corrosion condition evaluation was conducted for the tie beams and footings located in bents 19 through 24. The footings exhibited cracks and spalls, the majority of which were located on the south footings. Spalls were mostly located on the sides of the footings. Cracking was the predominant mode of deterioration on the tie beams. The concrete cover depth ranged from 71 to 121 mm for the tie beams and from 58 to 108 mm for the footings. A corrosion potential survey of the members revealed a few areas where the potentials were more negative than -350 mV CSE. These areas were typically found in the proximity of cracks or construction joints.

4.3.2.2. CP Information

The tie beam and the three footings in bent 20 were protected with arc-sprayed titanium. The arc-sprayed titanium anode was installed on the entire surface of the tie beam and the footings, with the exception of the bottom surface of the footings. The total surface area covered with the titanium anode was approximately 127 m^2. The instrumentation consisted of three silver-silver chloride reference cells and two null probes. Two reference electrodes were embedded in the footings and one reference electrode was embedded in the tie beam. One null probe was installed in one of the footings and the other in the tie beam.

Before the anode was applied, spalls and cracks were repaired and the concrete surface was sandblasted.

4.3.2.3. Field Evaluations

CONCORR, Inc., personnel were present during the initial energization of the system; subsequent evaluations were performed on the following dates:

Energization	October 7, 1997	
First evaluation	December 17 and 18, 1997	~ 2 months old
Second evaluation	February 9 to 11, 1998	~ 4 months old
Third evaluation	April 1 to 3, 1998	~ 6 months old
Fourth evaluation	June 3 to 6, 1998	~ 8 months old
Fifth evaluation	November 9 to 12, 1998	~ 13 months old

4.3.2.4. Findings

System Component Evaluation

During energization of the system, all components, with the exception of the RMU, were functioning properly. By the time of the second evaluation, the RMU problem had been rectified. The DC electrical continuity data erroneously indicated that there was a lack of continuity. This was attributed to the flow of corrosion currents in the reinforcing steel when the system was off.

System Performance

A visual survey of the condition of the arc-sprayed titanium was conducted during two evaluations (second and fifth). During the second evaluation, sprayed titanium was observed to have disbonded at the south end of the tie beam and at the sides of the footing. During the last evaluation, the condition of the sprayed titanium had deteriorated significantly. Approximately one-third of the coating had disbonded, exposing the concrete surface. At the time of the survey, it was raining and water was observed under the titanium coating.

The average concrete current density for the field evaluations ranged from 24.11 to 44.64 mA/m^2. Of the three reference electrodes, one never exceeded 100 mV, one exceeded 100 mV in each evaluation, and one varied from negative polarization to values in excess of 100 mV. Considering the excessive disbondment of the coating, it is expected that CP current is only being impressed in areas of good bonding, hence the variation in the polarization of the three reference electrodes. Also, the current densities impressed on this system are significantly higher than those encountered in the protection of steel embedded in concrete. Lack of polarization of the steel at such high current densities is indicative of either non-uniform current distribution by the anode or current leakage into the ground through the bay water.

4.3.2.5. Conclusions

The anode material in this system had significantly deteriorated and the system was not considered to be functional.

5.0. CONDUCTIVE COATING-BASED IMPRESSED-CURRENT CP SYSTEMS

Two conductive paint impressed-current systems were evaluated in this study. Both systems were installed on bridge substructure elements and both were located in Virginia. Pertinent information is provided in table 5-1:

Table 5-1. Conductive Coating-Based Impressed-current CP Systems

Structure Name and Location	Year CP System Installed	Element Protected	Area Protected	Instrumentation	Age at Last Evaluation	Average Chloride Ion Content of Steel Depth (ppm)
Maury River Bridges, Lexington, VA	1991 & 1992	14 piers & pier caps	1530 m^2	2 reference cells per zone	4 years	281 in southbound structure
James River Bridge, Richmond, VA	1987	93 hammerhead pier caps	7900 m^2	1 reference cell & potential wells	9 years	394

Note: Chloride ion content information was obtained from cores collected during this study.

5.1. Maury River Bridge, Lexington, Virginia

The Maury River Bridge on I-81 is located in Rockbridge County in Lexington, Virginia.

5.1.1. Structure Information

The bridge comprises one northbound and one southbound structure. Each structure carries two lanes of traffic and is supported by seven piers. The length and width of each structure are 215 m and 8.8 m, respectively. Construction of the bridge was completed in 1967.

Significant corrosion-induced delaminations (more than 14 percent) and spalls were encountered on the piers of the two bridges during a survey conducted in 1991. The distress on the piers was due to leakage of chloride-laden water through the joints.

5.1.2. CP Information

The piers were cathodically protected with an impressed-current system. The CP systems on the northbound and southbound structures were installed in November 1991, and July 1992, respectively.

The CP system utilized platinized wire as the primary anode and a conductive carbon-based coating as the secondary anode. For aesthetic purposes, a topcoat of white paint was applied to the black conductive coating.

The CP systems on the two structures are controlled by two 7-circuit, full-wave, unfiltered rectifiers. Each circuit controls one pier. Both rectifiers are located on the south end of the southbound structure. Two embedded graphite reference cells were installed in each pier for monitoring purposes.

Delaminated concrete was removed from the pier caps and repairs were performed using shotcrete.

5.1.3. Field Evaluations

Evaluations were performed on the following dates:

First evaluation	March 2, 1995	~ 3 year old
Second evaluation	June 12 and 13, 1996	~ 4 years old

5.1.4. Findings

System Component Evaluation

Electrical continuity testing using the DC technique detected continuity among all expected elements with one exception: Cell 2 on circuit 3 of the southbound rectifier had a discontinuous ground. The anode-to-structure data indicated that there were no shorts between the anode and the structure steel.

The AC resistance measurements between the anode and ground ranged from 13 to 89 ohms, significantly higher than values reported earlier (1.65 to 2.30 ohms). The significant increase in AC resistance with time may be due to anode degradation or a lower moisture content at the concrete-paint interface. It is widely accepted that AC resistance between conductive paint anode and system ground is very dependent on the amount of moisture at the concrete-paint interface.

Instant-off potential measurements made using the peak-hold method and the manual interrupt method differed significantly. Further evaluation of the system indicated the presence of AC noise circulating in the system wiring even when the rectifier was powered off. The magnitude of the AC noise correlated well with the increase in AC resistance between the reference cells and their respective grounds. The magnitude of the AC noise in some reference cells exceeded 600 mV. When AC noise is present, the manual method of measuring instant-off potentials is preferred because the actual value of the potential (minus potential drop) is measured after the system current has been interrupted. The actual value reduces the impact of AC noise on the measurement.

The AC resistance between all reference cells and their respective grounds was less than 10,000 ohms during the first evaluation. No AC resistance data were collected in the second evaluation.

The current meter on the rectifier for the southbound structure was malfunctioning and did not provide an accurate reading of the current.

System Performance

During both evaluations, the current settings for the southbound structure were found to be much lower than those for the northbound structure, even though the currents were adjusted to higher levels at the end of each evaluation. The current density in the as-found condition during each evaluation varied as follows:

Table 5-2. Current Density Variation

Structure	**Current Density Range (mA/m²)**	
	1st Evaluation	2nd Evaluation
Northbound	1.0 to 3.0	1.0 to 3.0
Southbound	0.2 to 1.0	0.5 to 1.3

Each structure was instrumented with a total of 14 reference cells. All reference cells, except one during the first evaluation and two during the second evaluation on the northbound structure, exceeded 100 mV during depolarization testing. On the southbound structure, three reference cells during the first evaluation exceeded 100 mV during depolarization testing and five did so during the second evaluation. Depolarization measured by three reference cells in the northbound structure exceeded 300 mV during both evaluations. One of these cells measured a depolarization of 599 mV during one evaluation. Two other reference cells from the northbound structure exceeded 300 mV in one of the two evaluations. Whereas, depolarization of only one reference cell from the southbound structure during the second evaluation exceeded 200 mV.

During the first evaluation, the exterior condition of the conductive paint and the overcoat was observed to be generally good, with the exception of some peeling, cracking, and bleeding of the black conductive paint from cracks in the overcoat. Visual observations during the second evaluation revealed that larger areas of the paint experienced deterioration. Blistering and disbondment were also observed during the second evaluation and some of the blisters contained water.

5.1.5. Conclusions

The majority of the piers on the northbound structure were receiving adequate protection, whereas the majority of the piers on the southbound structure were not receiving adequate protection. The conductive paint anode was deteriorating with time and the efficacy of the system was expected to decrease with time.

5.2. Route I-95 Over James River, Richmond, Virginia

The James River Bridge on I-95 was completed in 1957.

5.2.1. Structure Information

The bridge has 51 spans, with a total length of about 1.2 km and a roadway width of 24.4 m. There are three lanes each in the northbound and southbound directions. The substructure consists of 100 reinforced concrete piers with hammerhead-style pier caps each having approximately 79 m^2 of surface area.

Before rehabilitation, 80 to 90 percent of the surface area of several hammerhead pier caps was reported to be delaminated. Corrosion-induced deterioration was caused by saltwater run-off through leaking deck joints.

5.2.2. CP Information

A conductive-paint CP system was installed on 93 pier caps in 1987. The CP system utilized platinized wire as the primary anode and a conductive carbon-based coating as the secondary anode. A topcoat of gray acrylic paint was applied to cover the black conductive coating for aesthetics purposes.

As part of the CP system, 24 four-circuit constant-current rectifiers were installed on the railing of the northbound lane. Each rectifier provided power to four pier caps (except for rectifier #1, which powered two pier caps, and rectifier #14, which powered three pier caps). For monitoring purposes, each pier cap had an embedded molybdenum-molybdenum oxide reference cell and a number of potential wells in the conductive coating that could be used for obtaining potential measurements with an external reference cell.

Before the installation of the CP system, major rehabilitation consisting of extensive concrete removal and shotcrete repairs was performed.

5.2.3. Field Evaluations

Evaluations were performed on the following dates:

First evaluation	February 27 and March 15, 1995	~ 8 years old
Second evaluation	July 10 and 11, 1996	~ 9 years old

During the first evaluation, rectifier data were collected from 14 of the 24 rectifiers; a more detailed evaluation was performed only on piers protected by 4 rectifiers due to logistics and cost constraints. During the second evaluation, rectifier data were collected from 21 rectifiers and a more detailed evaluation was performed on piers protected by 10 rectifiers.

5.2.4. Findings

System Component Evaluation

The rectifier meters, particularly the current output meters, were generally found to be unreliable. The DC electrical continuity testing suggested that many of the reference cell grounds were not continuous with respect to their system grounds. The AC resistance between the reference cells and their respective grounds for many reference cells exceeded 100,000 ohms, and AC noise on many of the reference cells was excessive. The majority of the embedded reference cells were considered to be unreliable and were not used in the first evaluation. During the second evaluation, depolarization testing was performed with 38 embedded reference cells. Two reference cells did not exhibit any change in potential with the system power off; two exhibited acceptable behavior; and the remaining reference cells exhibited polarization in the wrong direction.

A 1993 evaluation report[5] indicates that numerous rectifier circuit cards have been replaced due to lightning strikes on the rectifiers. The placement of the rectifiers on the bridge railings makes them susceptible to lightning strikes.

The AC resistance between the anode and the system ground for many of the zones was much larger than expected and varied from 2 to 14 ohms (for piers 1 through 14) during the first evaluation. The AC resistance between the anode and the system ground increased with time for the same piers, with the exception of one pier. During the second evaluation, it varied from 5 to 23 ohms. The AC resistance for pier 12 decreased between the two evaluations.

System Performance

The depolarization data collected from the embedded reference cells were not considered to be reliable. Depolarization data were collected using external reference cells from windows established in the paint for that purpose. These data were only collected from windows in areas where the condition of the anode was judged to be reasonably good. Depolarization in these areas met the 100-mV criterion.

During the first evaluation, 12 of the 81 zones were operating at or near the maximum output voltage (30 V) of the rectifier and, during the second evaluation, 15 of the 81 zones tested were operating at or near the rectifier maximum. During the second evaluation, 35 of the 81 zones were operating in excess of 20 V. These high voltages are indicators of high circuit resistance. The BEMF were also very high for most of the zones. During the first evaluation, only 2 of the 81 zones tested had a BEMF in a generally expected range of 0.5 to 3 V. During the second evaluation, 15 of the 81 zones tested had a reasonable BEMF. Of these 15 zones, 2 zones were operating at an output voltage of less than 1 V and 5 were operating at maximum voltage with no current output. In many cases, BEMF voltages were in excess of 10 V, indicating very high anode polarization. This is a precursor to deterioration of the anode and damage to the concrete-paint interface.

The overall condition of the conductive coating and the overcoat was fair to poor during the first evaluation and it worsened during the second evaluation. Paint failure was evident on almost all piers in the form of cracking, peeling, coating disbondment, bleeding of conductive paint through the overcoat, and blistering.

The deteriorated condition of the paint in conjunction with the high output voltages and the high BEMFs suggest that the paint is not effective in distributing the current evenly throughout the protected area and the current is concentrated in areas where the anode is still intact.

Based on the condition of the conductive-paint system, the owners decided to remove the system and replace it with a galvanic zinc system.

5.2.5. Conclusions

The system had reached the end of its useful service life. It should be noted that a significant amount of concrete had been replaced before the installation of the conductive paint system.

6.0. CONDUCTIVE POLYMER-BASED IMPRESSED-CURRENT CP SYSTEMS

Two conductive polymer-based systems were included in this study. The system in West Virginia used conductive polymer in slots cut on the deck, whereas the system in Minnesota used mounds of conductive polymer placed on the deck surface under an overlay and in slots on the sidewalk. The system in West Virginia is classified as a slotted conductive polymer system. Although the system in Minnesota has both a mounded and slotted conductive polymer application, the mounded system is installed on a larger surface area of the bridge deck and the slotted system is installed on a smaller area on the sidewalks. Also, no instrumentation was installed in the slotted system in Minnesota to evaluate its effectiveness.

6.1. Slotted Conductive Polymer

Pertinent information on the slotted conductive polymer system is provided in table 6-1:

Table 6-1. Slotted Conductive Polymer-Based Impressed-current CP Systems

Structure Name and Location	Year CP System Installed	Element Protected	Area Protected	Instrumentation	Age at Last Evaluation	Average Chloride Ion Content of Steel Depth (ppm)
I-64 Bridge, Charleston, WV	1985	Deck	26,128 m^2	1 reference cell per zone	12 years	397

Note: Chloride ion content information was obtained from cores collected during this study.

6.1.1. I-64 Bridge, Charleston, West Virginia

The I-64 bridge carries eastbound and westbound traffic on Interstate 64 in Kanawha County, Charleston, West Virginia.

6.1.1.1. Structure Information

The bridge consists of 4 travel lanes and 26 simple spans, with a total length of 1217 m. Construction of the bridge was completed in 1974.

In August 1982, a corrosion condition evaluation of the structure determined the extent of the damage due to reinforcement corrosion. A visual and delamination survey was performed on 9197 m^2 of deck surface area. Approximately 1 percent of the tested deck area was delaminated or spalled. All but one of the 21 concrete cover measurements taken exceeded 51 mm. The chloride content at a 13-mm nominal depth was in excess of 1700 ppm and at a 63-mm nominal depth it was below the chloride threshold limit (260 ppm).

6.1.1.2. CP Information

Between 1984 and 1985, a non-overlay slotted anode system was installed on the bridge deck. The system consisted of platinized niobium wire primary anodes that were placed in slots longitudinally, and carbon strand secondary anodes that were placed in slots transversely. The slots were 13 mm wide and 19 mm deep. The transverse slots were spaced 0.30 m on center. After the anodes were placed, the slots were filled with a conductive polymer grout. In 1992, delaminations found on the deck were repaired and several components of the CP system were refurbished.

The CP system was installed to control corrosion on 26,128 m^2 of concrete surface area, which was divided into 46 zones controlled by 6 rectifiers. Each zone was instrumented with one silver-silver chloride reference cell. The system was equipped with an RMU that reportedly had not functioned as expected.

6.1.1.3. Field Evaluations

Evaluations were performed on the following dates:

First evaluation	October 22 and 23, 1996	~ 11 years old
Second evaluation	October 8 to 10, 1997	~ 12 years old

6.1.1.4. Findings

System Component Evaluation

The last evaluation was conducted after the system had been operating for 12 years. Several problems that were found in the first evaluation had been corrected by the time of the second evaluation. The electronic boards that were missing in 10 zones in the first evaluation had been installed. In addition, the five zones that were found to be receiving marginal protection from the CP system in the first evaluation were receiving adequate current and voltage output in the latest evaluation. The problem with the rectifier multiplier for measuring current output had also been corrected.

Resistors were found to be connected between the reference cell and the reference cell grounds. There was an apparent lack of electrical continuity between reference cell grounds and system grounds, particularly for the zones controlled by rectifiers 3 and 4. The apparent lack of continuity does not seem to impact potential measurement. Approximately 25 percent of the reference cells exceeded 10,000 ohms. No difference in performance could be identified between the reference cells that met the AASHTO T-29[4] limit criterion of 10,000 ohms and those that did not.

System Performance

The current density for both evaluations varied from 2.5 to 11.5 mA/m^2 and averaged 5.95 mA/m2. The rectifier output voltage and the BEMF were in the acceptable range. The 100-mV polarization decay criterion was achieved at more than 90 percent of the locations. The polarization at a few locations was excessively high.

Although not extensive, some deterioration of the conductive polymer in the slots and the concrete along the edge of the slots was noted. In some locations, the conductive polymer had failed and was missing from the slots; in other areas, acid attack on the concrete at the edges of the slots was observed. The observed damage was not sufficient to impact the performance of the system. It should be noted that the system had been rehabilitated in 1992 and such deterioration had been addressed.

6.1.1.5. Conclusions

All system components were performing satisfactorily. Based on the results of the depolarization testing, it may be concluded that the system was providing adequate protection. Although the system was 12 years old, a significant rehabilitation of the system components was performed at the age of 7 years.

6.2. Mounded Conductive Polymer

Pertinent information on the mounded conductive polymer system is provided in table 6-2:

Table 6-2. Mounded Conductive Polymer Impressed-current CP Systems

Structure Name and Location	Year CP System Installed	Element Protected	Area Protected	Instrumentation	Age at Last Evaluation	Average Chloride Ion Content of Steel Depth (ppm)
42nd St. over I-35 Minneapolis, MN	1983	Deck	976 m^2	1 reference cell & 1 or 2 corrosion probes per zone	15 years	NA

Note: Chloride ion content information was obtained from cores collected during this study.
NA - not available

6.2.1. 42nd Street Bridge over I-35, South Minneapolis, Minnesota

The 42nd Street bridge over I-35 W is located in South Minneapolis, Minnesota.

6.2.1.1. Structure Information

It comprises four spans and four travel lanes, with an overall length of 61 m and a width of 16 m. Construction of the bridge was completed in 1964.

Before rehabilitation, a condition survey revealed approximately 37 m^2 of delaminated and spalled concrete and corrosion potentials more negative than -400 mV CSE near the end approach joints.

6.2.1.2. CP Information

When the concrete repairs were completed, two different types of systems using rigid conductive polymer anode material were installed in 1983.

A rigid conductive polymer mound system was installed on the deck. Platinized niobium copper wires (PT) and high-purity carbon strands were used as the primary anodes. The PT wires were placed in the transverse direction on the repaired deck at two locations on the end spans and at four locations on the center spans. The carbon strands were placed in the longitudinal direction at a 0.46-m spacing in zones 1 and 2 and a 0.30-m spacing in zones 3 and 4. Subsequently, the rigid conductive polymer was placed over the entire length of the primary anodes in the form of a mound.

A slotted system was installed on the sidewalks. The PT wires and carbon strands were placed in slots cut in the sidewalk and then the slots were backfilled with rigid conductive polymer. The primary anodes were placed in the same configuration as the mounded system, except that a 0.30-m spacing between the carbon strands was used in all zones.

In each span, the slotted and the mounded system were combined to form a zone. Each zone was instrumented with a silver-silver chloride reference cell and a current probe placed in the deck. One additional current probe was installed in each end span (zones 1 and 4) at the level of the bottom mat reinforcing steel.

6.2.1.3. Field Evaluations

Evaluations were performed on the following dates:

First evaluation	September 19 and 20, 1994	~ 11 years old
Second evaluation	July 31, 1996	~ 13 years old
Third evaluation	May 11 and 12, 1998	~ 15 years old

6.2.1.4. Findings

System Component Evaluation

Electrical continuity data and AC resistance data were in the acceptable range, with the exception of the AC resistance between reference cells and their respective grounds. During the first evaluation, AC resistance for two of the cells exceeded 10,000 ohms, with one of them measuring 100,000 ohms. With each trip, the AC resistance of the reference cells kept increasing, and by the third evaluation, all reference cells had exceeded 10,000 ohms. There was no apparent impact of the high resistance on the measurement of the potentials by these reference cells.

The rectifier meter for measuring output voltage and current was not functioning and was in need of replacement.

System Performance

Three field evaluations were conducted on this system. The last evaluation was conducted after the system had been in service for about 15 years. The average concrete current density obtained in the three evaluations ranged from 2.26 to 2.91 mA/m^2. The 100-mV polarization decay criterion was only achieved in zone 1 in the first two evaluations (after the system had been in service for 11 and 13 years, respectively). During the last visit, the rectifier was found to be powered down and a failed fuse was found in zone 3. Also, two of the four instrumentation junction boxes were not accessible. Thus, only zones 1 and 3 were evaluated after the system was re-energized. Neither of these zones exhibited 100 mV of polarization in 4 hours. The BEMF for zones 3 and 4 was noted to be low during all three visits and the BEMF for zones 1 and 2 was also low during the last visit. With the exception of one corrosion probe (zone 4 top), all corrosion probes exhibited a change in the magnitude or a reversal of current through the probe upon system power off.

A 1.5-m^2 hollow-sounding area was detected in zone 4 during the last evaluation. The cause of this was not determined. Hollow-sounding areas were also detected on the sidewalk. Signs of conductive polymer failure in the slots and acid generation on the concrete adjacent to the slots were visible. The system had been operated at current densities much lower than those generally encountered in the mitigation of corrosion in reinforced concrete structures. Increasing the current density on these systems is expected to result in the generation of acid at the anode/concrete interface. The acids can lead to deterioration of the concrete.

6.2.1.5. Conclusions

The reference cells were drying up as indicated by the increase in resistance with time. The results of the depolarization testing suggested that the system was not providing adequate protection at the low current densities at which they were being operated. It should be noted that the corrosivity of the bridge deck was mild at the time of the installation of the system.

7.0. COKE BREEZE-BASED IMPRESSED-CURRENT CP SYSTEMS

Two coke breeze-based systems installed in Canada and one installed in California were included in this study. The system in California was installed in only one zone with several other systems. Pertinent information on these systems is provided in table 7-1:

Table 7-1. Conductive Coke Breeze-Based Impressed-current CP Systems

Structure Name and Location	Year CP System Installed	Element Protected	Area Protected	Instrumentation	Age at Last Evaluation	Average Chloride Ion Content of Steel Depth (ppm)
East Duffins Creek Bridge, Ontario, Canada	1991	Deck	612 m^2	3 reference cells & 4 reference probes	5 years	1793
Schomberg River Bridge, Ontario, Canada	1987	Deck	604 m^2	3 reference cells & 4 reference probes	9 years	4160
Upper Salt Creek Bridge, Redding, CA	1988	Deck	223 m^2	Potential wells	8 years	NA

Note: Chloride ion content information was obtained from cores collected during this study.
NA - not available

7.1. East Duffins Creek Bridge on Highway 7, Pickering, Ontario, Canada

The East Duffins Creek Bridge carries two lanes of Highway 7 over East Duffins Creek in Pickering, Ontario, Canada.

7.1.1. Structure Information

The bridge has a total length of 56 m, a total width of 13 m, and a deck surface area of 612 m2. Each travel lane is 5.5 m wide, with a 0.9-m sidewalk. Construction of the East Duffins Creek Bridge was completed in 1973.

Before the CP system was installed, the deck had delaminations and patched areas over approximately 2 percent of its area and 17 percent of the deck area was determined to have a high probability of active corrosion based on corrosion potential measurements. However, the average chloride ion content at the level of the reinforcing steel was less than the minimum threshold level required to initiate corrosion.

7.1.2. CP Information

In 1991, an impressed-current CP system, powered by a single-circuit rectifier, was installed on the travel lanes of the bridge deck. The anode system comprised a 40-mm-thick conductive coke breeze asphalt layer and 16 Durco Type 1 Pancake anodes. The conductive layer was overlaid with 40-mm-thick asphaltic concrete wearing surface. Three embedded graphite reference cells and four graphite voltage probes were installed for monitoring purposes.

Before the CP system was installed, unsound concrete and patching material were removed and repairs were performed using conventional concrete.

7.1.3. Field Evaluations

Evaluations were performed on the following dates:

First evaluation	May 11 and 12, 1995	~ 4 years old
Second evaluation	October 29 and 30, 1996	~ 5 years old

7.1.4. Findings

System Component Evaluation

All rebar probe grounds were found to be continuous to their respective system grounds. For proper operation of the voltage probes, the Ministry of Transportation of Ontario (MTO) believes that the probe-to-system ground resistance should not exceed 30 ohms and the probe-to-anode resistance should range from 10 to 15 ohms. Only one of the four voltage probes during the first evaluation met both of the requirements. During the second evaluation, none of the voltage probes met either of the requirements.

Anode-to-system ground resistance and the reference cell-to-reference cell ground resistance were in the acceptable range.

System Performance

The last evaluation was conducted when the system was in its fifth year of operation. No visually observable damage was detected in either evaluation and the asphalt overlay appeared to be well bonded to the concrete deck. The system was operated at an average concrete current density of 1.96 mA/m^2.

Polarization decay data obtained during the first evaluation indicated that complete decay did not occur within 4 hours. Thus, during the second visit, a 20-hour potential decay test was conducted. The average polarization decay was 96 mV and 190 mV for the first and second evaluations, respectively.

The instant-off potential for the voltage probes, with the exception of one during the first evaluation, did not fall in the range (-0.80 to -1.25 V) prescribed by MTO for proper operation. The remainder of the potentials were more positive than -0.80 V. MTO considers potentials more positive than -0.80 V to be indicative of insufficient protection.

The total chloride ion content at the rebar level was found to be 14 to 18 times greater than the minimum threshold level required to initiate corrosion. This CP system was considered to be performing satisfactorily, although the voltage probes cannot be relied upon for monitoring purposes.

7.1.5. Conclusions

With the exception of the voltage probes, the major components of the CP system were observed to be functioning normally. The voltage probes did not meet any of the requirements specified by MTO. The results of the depolarization testing indicated that the system was providing adequate protection.

7.2. Schomberg River Bridge on Highway 27, Toronto, Ontario, Canada

The Schomberg River Bridge carries Highway 27 over the Schomberg River in Simcoe County, Ontario, Canada.

7.2.1. Structure Information

The bridge is a semi-continuous reinforced concrete structure with a total length of 66 m, a total roadway width of 9.1 m, and a total deck surface area of 604 m^2. There is one northbound and one southbound lane; each lane is 4.6 m wide, with a 0.9-m sidewalk. Construction of the bridge was completed in 1966.

A corrosion condition evaluation of the bridge deck was conducted in July 1985. The results showed that 8 percent of the bridge deck was delaminated and approximately 19 percent of the deck area had a high probability of active corrosion (based on criteria provided in ASTM C-876).[6] The total chloride content was determined to be greater than 200 ppm by weight of concrete to a depth of 90 mm. Clear concrete cover over reinforcing steel varied from 35 mm to 60 mm.

7.2.2. CP Information

In 1987, a conductive bituminous overlay CP system, powered by a single-circuit rectifier, was installed on the bridge deck. The system consisted of iron pancake anodes (primary anodes) and a 40-mm-thick modified coke breeze overlay (secondary anode). A 63-mm-thick asphaltic riding surface placed on the coke breeze overlay protected the anode system. Three embedded graphite reference cells and four graphite voltage probes were incorporated in the system for monitoring purposes.

7.2.3. Field Evaluations

Evaluations were performed on the following dates:

First evaluation	May 8 and 9, 1995	~ 8 years old
Second evaluation	October 29 and 30, 1996	~ 9 years old

7.2.4. Findings

Electrical continuity between reference cell grounds and system grounds and the absence of shorts between the anode and system ground and the voltage probe and system ground were verified. The AC resistance between the anode and the system ground, reference cells and reference cell grounds, and voltage probes and system ground were in the acceptable range during the first evaluation. Resistance between two voltage probes and their respective grounds exceeded the 30-ohms limit during the second evaluation. The AC resistance between all voltage probes and the anode was greater than 15 ohms.

System Performance

No visually observable damage was detected in either evaluation, and the asphalt overlay appeared to be well bonded to the concrete deck. The system operated at an average concrete current density of 1.84 mA/m^2. Polarization decay was well in excess of 100 mV in 4 hours. One of the four voltage probes did not meet the MTO resistance criteria for reliability and three of the four probes, including the unreliable one, had more positive potentials than allowed by the MTO guidelines. For proper operation of the system, MTO guidelines require that the instant-off potentials of the voltage probes be maintained between -0.80 and -1.25 V. Approximately 8 years after the CP systems had been installed, the total chloride ion content at the rebar level was found to be 3 to 11 times greater than the threshold level required to initiate corrosion at the time of the first field evaluation.

Although the voltage probe data were outside the range permitted in MTO guidelines, the polarization data, system operation data, and visual condition of the system and the deck indicated that the CP system was performing satisfactorily.

7.2.5. Conclusions

The system was performing satisfactorily and was providing adequate protection. The performance of the voltage probes was suspect, at best.

7.3. Upper Salt Creek Bridge on Southbound I-5, Redding, California

The Upper Salt Creek Bridge carries southbound I-5 in Redding, California.

7.3.1. Structure Information

The bridge is 11.4 m long and 3.6 m wide, with a deck surface area of 446 m^2. Construction of the Upper Salt Creek Bridge was completed in 1966.

7.3.2. CP Information

A 38-mm-thick layer of Ashbury #99 type coke breeze was used at the primary anode and the power connection to the coke breeze was achieved through type II high silicon cast-iron plates installed on the deck. A 64-mm-thick concrete asphalt overlay was placed on the coke breeze to provide a riding surface.

No embedded reference cells or rebar probes were installed in the system. However, potential wells were installed on the bridge deck to facilitate potential measurements using an external reference electrode. A constant voltage rectifier was used to power the system.

7.3.3. Field Evaluations

Evaluations were performed on the following dates:

First evaluation	October 31 to November 4, 1994	~ 6 years old
Second evaluation	November 26 and 27, 1996	~ 8 years old

7.3.4. Findings

System Component Evaluation

No instrumentation was installed in this system. Built-in voltage and current meters did not provide accurate readings. During the second evaluation, the system was found powered off . The power to the system was turned on and rectifier data were collected and polarization development testing was performed.

System Performance

The concrete current density during the two evaluations varied from 1.4 to 2.3 mA/m2. The output voltage and BEMF were in the acceptable range and the anode-to-system AC resistance averaged 0.41 ohms. During both evaluations, the polarization development or decay exceeded 100 mV in all wells tested.

7.3.5. Conclusions

The system was providing adequate protection.

8.0. ZINC-BASED GALVANIC CP SYSTEMS

Zinc-based galvanic systems have found application on substructural elements of marine structures. The State of Florida has concluded that the only cost-effective method to protect marine substructures is galvanic CP. Zinc anode is used in several different forms, such as arc-sprayed zinc, zinc foil with an adhesive, and expanded zinc sheets in jackets or with compression panels. Of the different types of zinc applications, the arc-sprayed zinc, zinc with adhesive, and expanded zinc with compression panels were evaluated in this study.

8.1. Arc-sprayed Zinc

Three arc-sprayed zinc systems were evaluated in this study. Pertinent information on them is provided in table 8-1:

Table 8-1. Arc-Sprayed Zinc Galvanic CP Systems

Structure Name and Location	Year CP System Installed	Element Protected	Area Protected	Instrumentation	Age at Last Evaluation	Average Chloride Ion Content of Steel Depth (ppm)
Queen Isabella Causeway, South Padre Island, TX	1997	Tie beam & footings in bent	127 m^2	3 reference cells & 2 null probes	13 months	457 in north footing
Howard Frankland Bridge, Tampa Bay, FL	1992	Deck soffit, prestressed beams, pile caps, & piles	11,148 m^2	Rebar probes & windows	5 years	488
7 Mile Bridge, Marathon, FL	1991 & 1996	Columns	NA	Rebar probes	7 years & 2 months	3124

Note: Chloride ion content information was obtained from cores collected during this study.
NA - not available

8.1.1. Queen Isabella Causeway, South Padre Island, Texas

The Queen Isabella Causeway is a 4.0-km-long bridge structure on PR 100 that links South Padre Island to the mainland of Texas at Port Isabel and spans the Laguna Madre.

8.1.1.1. Structure Information

The structure carries four lanes of traffic going east/west. It comprises 150 spans, 3 continuous steel plates, and 147 simple prestressed concrete girder spans. The spans are supported by 150 bents that are numbered from 1 to 150 from west to east. Construction of this structure was completed in 1973.

In 1997, a corrosion condition evaluation was conducted for the tie beams and footings located in bents 19 through 24. The footings exhibited cracks and spalls, the majority of which were located on the south footings. Spalls were mostly located on the sides of the footings. Cracking was the predominant mode of deterioration on the tie beams. The concrete cover depth ranged from 71 to 121 mm for the tie beams and from 58 to 108 mm for the footings. A corrosion potential survey of the members revealed a few areas where the potentials were more negative than -350 mV CSE. These areas were typically found in the proximity of cracks or construction joints.

8.1.1.2. CP Information

A galvanic arc-sprayed zinc CP system was installed on bent 22. The entire surface of the tie beam and the three footings, with the exception of the bottom surface of the footings, totaling approximately 127 m^2, were protected. The instrumentation consisted of three silver-silver chloride reference cells and two null probes. Two reference electrodes were embedded in the footings and one reference electrode was embedded in the tie beam. One null probe was installed in one of the footings and the other in the tie beam.

The spalls and cracks were repaired and the concrete surface was sandblasted before the application of the anode.

8.1.1.3. Field Evaluations

CONCORR, Inc., personnel were present during the initial energization of the system; subsequent evaluations were performed on the following dates:

Energization	October 7, 1997	~ 0 years old
First evaluation	December 17 and 18, 1997	~ 2 months old
Second evaluation	February 9 to 11, 1998	~ 4 months old
Third evaluation	April 1 to 3, 1998	~ 6 months old
Fourth evaluation	June 3 to 6, 1998	~ 8 months old
Fifth evaluation	November 9 to 12, 1998	~ 13 months old

8.1.1.4. Findings

System Component Evaluation

During energization of the system, the RMU system was not functioning properly. By the time of the second evaluation, the RMU problems had been rectified. Electrical continuity was detected between reference cell grounds and system grounds. The AC resistance between the reference cells and their respective grounds was lower than 10,000 ohms for all cells in all evaluations, with the exception of one cell in one evaluation.

System Performance

The performance of a galvanic CP can be evaluated by reviewing the current provided by the sacrificial anode and the polarization of the steel. The current output of the arc-sprayed zinc anode varied from 1.9 mA/m^2 to 3.8 mA/m^2 during the five evaluations. This level of current output for a galvanic system was considered to be acceptable.

Depolarization testing was performed using the three embedded reference cells during four of the five evaluations. During the second evaluation, one reference cell exceeded the 100-mV criterion in 4 hours and one came very close to the criterion (95 mV) in 4 hours. These two reference cells continued to exhibit similar behavior in the remaining three evaluations. Both cells measured depolarizations in excess of 100 mV when allowed to depolarize up to 22 hours.

The third reference cell did not indicate 100 mV of depolarization in 4 hours during the second evaluation and it exhibited abnormal behavior. Immediately after the interruption of the CP current, it would measure potentials indicative of depolarization in excess of 100 mV. The measured potential would then become more negative with time and would result in lower levels of depolarization. This behavior was exhibited in two of the four evaluations. In the other two evaluations, it exhibited normal behavior and met the 100-mV requirement in 22 hours and 4 hours, respectively.

8.1.1.5. Conclusions

The results of the depolarization testing and the levels of output current indicated that the CP system was providing adequate protection.

8.1.2. Howard Frankland Bridge on I-275, Tampa, Florida

The Howard Frankland Bridge is part of I-275 and spans the Tampa Bay.

8.1.2.1. Structure Information

This four-lane bridge consists of 321 spans, with an overall length of 4838 m. Construction of the Howard Frankland Bridge was completed in 1960.

8.1.2.2. CP Information

The sacrificial CP systems installed on the Howard Frankland Bridge included the application of arc-sprayed zinc to approximately 11,148 m^2 of concrete surface, the installation of perforated zinc-sheet bulk anode systems on 67 piles, and the installation of bulk anodes on 20 bridge piers. The scope of this study was limited to the arc-sprayed zinc system; the other two systems were not evaluated.

The arc-sprayed zinc was applied to surface areas of select piles, pile caps, prestressed beams, and the soffit of the deck. The zinc application employed multiple spray passes to achieve a coating thickness of 15 to 20 mm. The connection of the anode to the reinforcing steel at all sites, except for bent 293 and span 292, was achieved by direct contact of the reinforcing steel at the areas where the rebar was exposed.

The instrumentation for the arc-sprayed zinc system was installed on select members and consisted of embedded rebar probes and anode windows. Embedded rebar probes consisted of a number 4 rebar segment with a surface area of 1290 mm^2 that can be connected or disconnected to the zinc coating. This allowed the measurement of current flow between the anode and the probes, and the performance of polarization and depolarization testing. Square sections of zinc anode measuring 0.093 m^2 (termed "windows") were isolated from the remainder of the arc-sprayed zinc anode. These windows were connected directly to the structure in a junction box, with provisions to allow disconnection and connection back to the structure for testing purposes. Current flow generated by the anode in the window could be measured by disconnecting the window and installing a current meter in series with the anode and the structure.

The test probes and the windows were installed on three piles (above the perforated zinc sheets in arc-sprayed zinc protected areas), two prestressed beams, four pile caps, and on one section of the soffit of the deck.

Before application of the arc-sprayed zinc, all delaminated concrete was removed. No concrete patch repairs were performed. A light silica sand abrasive blast was used to remove any mill scale, rust, dirt, or any other foreign material from the surface to be coated. The zinc application employed multiple spray passes to achieve a coating thickness of 0.38 to 0.51 mm. Connection of the anode to the reinforcing steel at all sites, except for bent 293 and span 292, was achieved by direct contact of the reinforcing steel at the areas where the rebar was exposed.

8.1.2.3. Field Evaluations

Evaluations were performed on the following dates:

First evaluation	March 24 and 25, 1995	~ 3 years old
Second evaluation	January 22 and 23, 1997	~ 5 years old

8.1.2.4. Findings

System Component Evaluation

The AC resistance between the probes and system grounds indicated that the probes were not shorted to the structural steel and were functional. Some of the connections to the zinc anode for instrumentation were exhibiting signs of corrosion and loss of zinc adjacent to it.

System Performance

At all test locations where probes were installed, approximately half of the probes were maintained in the "on" position (i.e., connected to the CP system) and the other half were maintained in the "off" position (i.e., disconnected from the system). At each location, probes that were powered on were used to conduct a depolarization testing. Subsequent to the depolarization testing, when the system was energized, the probes that were powered off were used to conduct polarization testing.

The current output density based on the current received by the probes averaged 5.93 and 4.72 mA/m^2 per steel surface area for the two evaluations, respectively. During the second evaluation, data from the instrumentation from one of the piles could not be collected. During the first evaluation, current in two probes was flowing in the opposite direction from what was expected. Measurements from these two probes were not included in the average. The current flow from the windows to the structural steel averaged 27.87 and 4.38 mA/m^2 of anode surface area in the two evaluations, respectively.

The results of the polarization and depolarization testing performed with the probes averaged 155 mV of potential shift in 4 hours during the first evaluation. Five of the 22 measurements did not exceed 100 mV. Two measurements exhibited shifts in the wrong direction and were not included in the average. During the second evaluation, the potential shift averaged 169 mV and 2 of the 21 measurements did not exceed 100 mV.

8.1.2.5. Conclusions

Considering the current output by the system after 5 years of operation and the results of the polarization/depolarization testing, it may be concluded that the system was providing adequate protection.

8.1.3. Seven Mile Bridge, Florida Keys, Florida

The Seven Mile Bridge is part of U.S.1 in the Florida Keys, Florida.

8.1.3.1. Structure Information

The bridge has 266 bents, an overall length of 10,931 m, and a deck width of 11 m that consists of two travel lanes. The substructure consists of 91-cm-diameter columns, which terminate in drilled shafts and struts between each column pair. There are two columns per bent, designated East and West. The reinforcement consists of epoxy-coated rebar. Construction of the bridge was completed in 1979.

8.1.3.2. CP Information

There were two applications of arc-sprayed zinc on the columns of the Seven Mile Bridge. The first application was made in 1991 on select columns. Additional columns were protected in 1996. Before application of zinc, delaminated concrete was removed and the surface that was to receive the arc-sprayed zinc was sandblasted to produce an acceptable profile on the concrete surface and to remove all epoxy coating from the reinforcing steel exposed in the excavated areas. No repairs were made in areas where deteriorated concrete had been removed. After sandblasting and before the application of the arc-sprayed zinc anode, the concrete surface was blown down with air to remove debris. The arc-sprayed zinc was then applied to the concrete surface and the exposed reinforcing steel. The negative connection of the sprayed zinc to the structure was achieved by spraying the zinc coating directly onto the exposed rebar.

Nine columns, three sprayed in 1991 and six sprayed in 1996, were instrumented by CONCORR, Inc., in 1996 during the first evaluation using the Florida DOT design for embedded probes. Each of these nine columns was instrumented with two embedded rebar probes. Each probe consisted of a number 4 rebar segment with a surface area of 1290 mm^2. The probes could be connected or disconnected to the column steel to perform polarization development/decay testing.

8.1.3.3. Field Evaluations

Evaluations were performed on the following dates:

First evaluation	February 28 and 29, 1996	~ 5 years/1 month old
Second evaluation	February 20, 1997	~ 6 years/1 year old
Third evaluation	May 22, 1998	~ 7 years/2 years old

8.1.3.4. Findings

System Component Evaluation

The AC resistance measurements made between the anode and the embedded probes indicated that the probes were not continuous to the anode. The resistance between the probes and the anode increased an order of magnitude between the first evaluation and the second evaluation and then leveled off.

System Performance

Of the two probes installed on each column, one was labeled the top probe and the other the bottom probe. During each evaluation, depolarization and polarization were performed on the top and bottom probes as follows:

8.2.1.4. Findings

System Component Evaluation

The DC electrical continuity testing performed before the energization of the system indicated that all reference cell grounds were continuous to their respective system grounds and to each other. The AC resistance of the reference cells to their respective grounds was measured in two of the three evaluations and was less than 10,000 ohms for all reference cells. The AC resistance between the anode and the system ground averaged 1.6 ohms for piers 1 and 3 and 4.6 ohms for pier 2.

System Performance

The adhesive that bonds the anode to the concrete surface is extremely water-soluble and any water intrusion between the zinc and the concrete surface results in dissolution of the adhesive and loss of bond. Water leaks along expansion joints resulted in failure of the anode at the ends of the pier caps immediately after installation. The anode at the end of the piers was replaced and installed vertically to reduce water intrusion between the zinc and the concrete surface. During system energization, air pockets were visible on the anode surface. In these areas, the anode was probably not making contact with the concrete surface. Visual survey during the first evaluation detected disbondment of the anode on the ends of some of the pier caps and a small section of anode (approximately 0.30 m long) had peeled off the concrete surface on the south end of pier 1. By the third evaluation, the damaged section of the anode on the south end of pier 1 had increased to approximately 1.2 m.

The current output per pier ranged from 1.66 to 4.45 mA/m^2. The average polarization decay in 4 hours for the first, second, and third evaluations was 107, 102, and 92 mV, respectively. In two of the three evaluations, 22-hour depolarization testing was performed and all reference cells exceeded 100 mV.

8.2.1.5. Conclusions

The anode was providing sufficient current to stop the ongoing corrosion on the pier caps. The life of the anode was dependent on the life of the adhesive and the consumption rate of the zinc.

8.3. Expanded Zinc Mesh and Bulk Anode

One expanded zinc mesh with a compression panel anode was evaluated in this study; its pertinent information is provided in Table 8-4:

Table 8-4. Expanded and Bulk Anode Galvanic CP Systems

Structure Name and Location	Year CP System Installed	Element Protected	Area Protected	Instrumentation	Age at Last Evaluation	Average Chloride Ion Content of Steel Depth (ppm)
Bryant Patton Bridges, St. George Island, FL	1995	Prestressed piles	171 piles	Reference cells & current probes in select piles	3 years	NA

NA - not available

8.3.1. Bryant Patton Bridges, St. George Island, Florida

The Bryant Patton Bridges link St. George Island to the mainland of Florida at East Point. These bridges span almost 1.6 km of the Appalachicola Bay in Franklin County.

8.3.1.1. Structure Information

The Bryant Patton Bridges consist of bridge number 490003 and bridge number 490004, which are designated as bridges 3 and 4, respectively. Bridges 3 and 4 have 296 and 560 prestressed piles, respectively. All piles are 0.51-m squares and were constructed with 20 prestressed tendons each. The tendons are spirally wrapped with number 5 gauge wire. The Bryant Patton Bridges were constructed in 1965.

In 1990, a corrosion condition evaluation of the structure revealed that 160 piles were deficient. An additional 17 piles were found to be deficient in 1991. Deterioration of concrete due to corrosion of the spiral wire and the prestressed strands was the most significant problem. The damage was concentrated in the splash zone.

8.3.1.2. CP Information

The CP system was installed in 1995 to control corrosion on 171 prestressed piles (59 piles in bridge 3 and 112 piles in bridge 4). The upper section of each pile was protected with arc-sprayed zinc. A total of 890 m^2 of concrete surface area was sprayed with zinc. The splash zone was protected by 1.14-m-high expanded zinc anode sheets clamped onto the concrete surface by recycled wood-plastic compression panels. The submerged zone was protected with 22.7-kg bulk zinc anodes.

Instrumentation was installed on two piles of bridge 3 and four piles of bridge 4. Two piles in each bridge were wired to remote data-acquisition units that were not functional. Cathodic protection was not installed on the other two remaining instrumented piles of bridge 4. These two piles (piles 4 and 5 in bent 64) served as the control members. Instrumentation consisted of five silver-silver chloride reference cells and five corrosion probes in each pile. Reference cells and corrosion probes were numbered 1 through 5 with increasing elevation. Reference cell 1 was located approximately 213 mm above the low-water mark and 213 mm below the bottom of the expanded zinc jacket; reference cell 5 was located approximately 1.52 m above the first reference cell and 150 mm above the top of the expanded zinc jacket.

8.3.1.3. Field Evaluations

Evaluations were performed on the following dates:

First evaluation	January 21 and 22, 1997	~ 2 years old
Second evaluation	February 24 and 25, 1998	~ 3 years old

8.3.1.4. Findings

System Component Evaluation

The AC resistance for four reference cells was in a very high range (150,000 to 800,000 ohms). Whereas the AC resistance between the anodes and the system grounds was in the acceptable range and averaged 1.6 ohms for the bulk anode and 26.0 ohms for the expanded zinc sheet anode.

System Performance

Current flow was measured from 40 non-instrumented piles (20 from each bridge) during each evaluation. The total current flow (bulk anode and the expanded zinc anode) averaged 15.2 mA and 12.3 mA for the first and second evaluations, respectively. If it is assumed that the effective concrete surface area protected by both anodes is the surface area of the pile from the bulk anode elevation to the top of the compression panel, the average currents would be equated to 3.3 and 2.7 mA/m^2 of concrete surface area, respectively. For the instrumented piles, the currents averaged 12.2 mA and 13.1 mA or 2.7 and 2.9 mA/m^2, respectively. The majority of the current was provided by the bulk anode. For the non-instrumented piles, an average of 70 to 90 percent for the instrumented piles and 72 to 79 percent of the total current was provided by the bulk anode. The average current received by the current probes ranged from 17 mA/m^2 of steel surface area at the lowest elevation to 33 mA/m^2 of steel surface area at the highest elevation when the system was energized.

The depolarization data were difficult to interpret due to interference from steel in the section of the pile that was submerged and extremely polarized. When the bulk and the expanded sheet anodes were disconnected, the steel in the submerged section started to depolarize and it interfered with the measurement of the static potential using the embedded reference cells. This interference was also dependent on the tide. Thus, data collected at different tide levels were different.

9.0. CONCLUSIONS

9.1. Discussion

The primary objective of this study was to determine the effectiveness of various materials and configurations when used as auxiliary anodes on highway structures through a long-term evaluation. The effectiveness of a material is judged by its ability to provide the cathodic protection current, its durability in the application environment, and its service life.

The capacity to provide the required CP current is controlled by the material's electrochemical properties. When an anode delivers the CP current, it reacts to the current flow by changing its surface potential. The magnitude of the change in its potential is termed "polarization." The magnitude of the polarization for the same level of current delivery is different for different anodes. The polarization of the anode governs at what current delivery level harmful byproducts such as chlorine gas are generated, which can result in the damage of concrete adjacent to the anode and/or the anode itself. Thus, every anode has a limiting current density below which it must be operated to ensure that harmful byproducts are not generated.

Durability of the material is the ability of the material to weather the application environment. Many anode materials deteriorate when exposed to certain environments, which compromises their ability to deliver the CP current. Visual observation of the condition of the anodes in service, where possible, provided information on the durability of the anode. The results of the anode-to-system ground resistance measurements and the polarization/depolarization testing provide insight into the health of the anode when considered in conjunction with the system current outputs.

Service life is the length of time the anode can provide the required CP current. The theoretical upper limit for service life is based on the amp-hours that a given quantity of anode can provide. Knowing the current output required during CP and the quantity of anode material, one can calculate the theoretical upper limit of service life. The theoretical upper limit is usually not accomplished in the real world. For metallic anodes such as zinc, the calculation of theoretical upper limit is accomplished by using Faraday's Law and the amount of zinc used as an anode. When anodes such as conductive paint are used, the calculation is a little more complex. The quantity of anode material in the paint (e.g., amount of carbon in the paint) governs the theoretical upper limit of the service life. For impressed-current anodes, many manufacturers provide this theoretical upper limit as the maximum life that can be expected from the anode, and galvanic anodes are often rated by the total weight of the anode or the thickness of the coating.

Other factors that can impact the service life of an anode material include the generation of byproducts that can impede the flow of CP currents and passivation of galvanic anodes. Although all factors discussed above impact the service life of an anode material, often one or more factors become the controlling factor(s) and they determine the performance of an anode material in a particular configuration in a particular environment.

9.2. Arc-sprayed Zinc Impressed-Current CP Systems

Four arc-sprayed zinc impressed-current CP systems were evaluated in this study. The age of the system at the last evaluation varied from 13 months to 8 years. Three of the four systems were under the age of 2 years. Two systems located in Oregon (Yaquina Bay Bridge and the Depoe Bay Bridge) were in a semi-marine environment. The zinc systems installed on the superstructure and the substructure elements were at a significant height above the water level and were not directly exposed to the bay water. They were exposed to chlorides in the air and some deicing salt used on the deck. In Texas, the zinc system on the Queen Isabella Causeway was directly exposed to the bay water and was located in the splash zone. The California system was located on the deck under an asphalt overlay and was exposed to deicing salts.

The Oregon systems were being operated at insufficient current densities (1 to 2 mA/m^2) and were not providing adequate protection. Also, the system in Depoe Bay may not have been functioning continuously to provide the protection needed. In both systems, the current outputs could have been increased to ensure adequate protection without impacting the system.

The Texas system was operating at an average current density of 15.15 mA/m^2 and was achieving adequate polarization. The band of whitish product at the bottom of the side faces of the footings was indicative of accelerated consumption of zinc anode in this area. It was suspected that when the tide came up and that portion of the anode was submerged in water, current from the anode was leaking into the bay water at a very large rate because the resistance of the bay water is very low. The anode in this section of the system was expected to be consumed much earlier than the rest of the system.

Unfortunately, system performance on California's Upper Salt Creek Bridge could not be evaluated due to lack of instrumentation. The system was putting out current at the rate of 2.2 mA/m^2.

Although the theoretical consumption rate of zinc is very low, several other factors may limit the service life of arc-sprayed zinc. Theoretically, a 0.50-mm-thick coating providing current at the rate of 10.75 mA/m^2 at a 70-percent level of efficiency would last approximately 22 years. Some researchers predict that the corrosion products generated by the consumption of zinc may eventually plug the pores in concrete and result in very high circuit resistance that would impact the ability of the system to provide effective protection. Also, due to the consumption of zinc over time, the bond between the zinc and concrete may be reduced and lead to failure of the system. In systems such as the one in Queen Isabella Causeway, wave action may abrade much of the zinc over time and reduce its overall service life.

Based on the performance of these arc-sprayed zinc systems to date, it is anticipated that these systems will be able to provide adequate protection for approximately 10 to 15 years.

9.3. Titanium-based Impressed-current CP Systems

9.3.1. Titanium Mesh Anode

Five CP systems utilizing the titanium mesh anode, ranging in age from 13 months to 12 years at the last evaluation, were included in this study. Four of the five systems were located in high deicing salt use areas and one was located in a marine environment. The titanium mesh system on the underside of the roadway deck of the Brooklyn Battery Tunnel experienced bond failure between the shotcrete overlay and the original deck concrete from the time of installation. This system was improperly installed and destined to fail. Thus its performance is not discussed here.

The four remaining systems were operating at current densities close to 10.75 mA/m2 and depolarization exceeded 100 mV in all operating reference cells except two in Wawecus Hill Road Bridge. Two of these four structures were instrumented with null probes and one with current probes. All operating null probes and current probes in the Wawecus Hill Road Bridge and the Columbia Road Bridge exhibited reversal of current at power off and all null probes installed on the Queen Isabella Causeway either exhibited reversal of current or zero current at power off. The results of the depolarization testing and probe currents indicate that the titanium mesh anode systems were applying sufficient current to provide adequate protection.

The theoretical service life of the titanium mesh anode is claimed to be 50 years. Based on the performance of the mesh anode in these four systems and the range of years that they have been in service, it is estimated that reasonable service life of the titanium mesh anode is probably in excess of 25 years.

9.3.2. Titanium Ribbon Anode

One titanium ribbon anode system was evaluated in this study. This structure was exposed to a deicing salt environment and the system had been operating for 9 years at the time of the last evaluation. Although the operating current density of the system was low (ranging from 2.9 to 3.3 mA/m^2), depolarization measurements at all embedded reference cells exceeded 100 mV. It should be noted that the reference cells were installed at the level of the new top mat, which was composed of epoxy-coated reinforcing steel.

With the titanium ribbon anode, design considerations require proper spacing between the ribbon anodes to ensure that the maximum anode current density is not exceeded when operating at 10.75 to 16.13 mA/m^2. Because the system is operating at a low-output current density, there is no concern with regard to exceeding the maximum anode current density.

9.3.3. Arc-Sprayed Titanium

Two experimental installations of arc-sprayed titanium anode were included in this study. Both systems were installed in only one of several zones in the two bridges. One system was installed on the superstructure and substructure elements of Depoe Bay Bridge in Oregon; the other was installed on the substructure elements of the Queen Isabella Causeway Bridge in Texas. The Depoe Bay Bridge was in a semi-marine environment and the Queen Isabella Causeway was in a marine environment. Both systems were approximately 1 year old at the time of the last evaluation.

The Depoe Bay Bridge system had been operated intermittently at an average current density of 1.0 mA/m^2 for 1 year at the time of the last evaluation. Depolarization measurements at all reference cells exceeded 100 mV in all evaluations, and the current in the null probes went to zero when the system was powered down. The effectiveness of this system was difficult to judge because it had not been operated on a continuous basis.

The system installed on the Queen Isabella Causeway was directly exposed to wave motion in the bay. It had suffered significant anode damage in 13 months of operation. The system was operating at very high current densities, varying from 24.11 to 44.64 mA/m^2. Depolarization measurements at only one of the three reference cells exceeded 100 mV. At one reference electrode, depolarization varied from negative to positive (i.e., in the wrong direction to the connection) and at times exceeded 100 mV. Based on the high current density in conjunction with the damage to the anode and lack of sufficient depolarization, it may be concluded that the system had failed. The arc-sprayed titanium anode is not durable in the marine environment.

9.4. Conductive Paint Impressed-current CP Systems

Two conductive paint impressed-current CP systems were evaluated. Both systems were installed on substructure elements (pier caps) exposed to deicing salt-contaminated water runoff from leaking joints. The ages of the systems at the time of the last evaluation was 4 and 9 years.

The four-year-old system was installed on the northbound and southbound structures of the Maury River Bridge in Lexington, Virginia. The system had experienced an increase to unacceptable levels of the circuit resistance between the anode and the system ground (13 ohms to 89 ohms) by the time of the first evaluation. At the time of the first evaluation, the condition of the paint anode was generally good, although some deterioration of the anode was observed. At the time of the second evaluation, an increase in the deterioration of the anode was noted. The northbound structure, which was operated at a higher current density (1.0 to 3.0 mA/m^2) than the southbound structure (0.2 to 1.3 mA/m^2), fared better in the depolarization testing.

Depolarization measurements at the majority of the reference cells on the northbound structure exceeded 100 mV; the majority of the reference cells on the southbound structure did not exceed 100 mV. Depolarization at a few reference cells on the northbound structure was extremely high and ranged from 300 to 600 mV.

The older system installed on the Route I-95 bridge over the James River in Richmond, Virginia, had already started to fail at the time of the first evaluation. By the time of the second evaluation, significant failure of the conductive coating had occurred. Many zones were operating at a maximum output voltage of 30 V. Replacement of the paint system began in 1999.

The durability of conductive paint is significantly lower than the theoretical service life of 20 years claimed for it. One of the two systems failed within 10 years and the other is expected to fail before reaching 10 years of operation. The 5- to 10-year service life of the conductive paint systems observed in this study is similar to that reported by others.[5] The conductive paints are water-based and can deteriorate when exposed to water.

9.5. Conductive Polymer-based Impressed-current CP Systems

One slotted and one mounded conductive polymer impressed-current CP system were included in this study. These systems were relatively older than most systems evaluated in this study. The slotted system was 12 years old and the mounded system was 15 years old at the time of the last evaluation.

The slotted system installed on the I-64 bridge in Charleston, West Virginia, needed rehabilitation at the age of 7 years. At 11 and 12 years, some deterioration of the anode in the slots was noted. Acid attack of the concrete at the edges of the slot was observed at a few locations and the anode had become brittle and failed at other locations. The magnitude of the anode deterioration and acid attack on the slot edges was not sufficient to impact the overall performance of the system. The need for repairs at 7 years and further deterioration at 12 years suggest that the anode was not very durable. At the time of the evaluations, the current output densities were varying significantly and ranged from 2.5 to 11.5 mA/m^2. At these current densities, 90 percent of the depolarization measurements exceeded 100 mV.

The mounded conductive polymer system was the oldest system evaluated in this study. This system included the use of conductive polymer in mound form on the bridge deck and in slots on the sidewalks. Where the conductive polymer was exposed in the slots on the sidewalks, failure of the anode was observed at many locations. The anode material had become brittle and failed in the slots, and signs of acid attack on the concrete at the edges of the slots were noted. The condition of the mounds could not be determined because the mounds were covered by the overlay. This system had been operating at a current density ranging from 2.26 to 2.91 mA/m^2. Depolarization measurements at most reference cells did not exceed 100 mV.

The conductive polymer anode is not very durable and exhibits very high potentials at low current densities, resulting in the generation of chlorine gas. Over time, the chlorine gas converts to an acid and attacks the concrete in the vicinity of the anode. Also, the polymer becomes brittle and fails in slots and loses its bond to the concrete. The estimated service life for this anode material is approximately 5 to 10 years.

9.6. Coke Breeze-based Impressed-current CP Systems

All three coke breeze systems were exposed to a deicing environment. Two of the three systems were located in Ontario in very similar environmental conditions; the third was located in Northern California. The ages of these systems ranged from 5 to 9 years at the time of the last evaluation.

In two of the three systems, all depolarization measurements exceeded 100 mV; in the third, the average depolarization at 20 hours was 92 and 190 mV. These systems were operating at current densities of around 2 mA/m^2.

In 5 to 9 years, the systems have not exhibited any signs of deterioration of the anode material. The service life of these systems is probably governed by the life of the riding surface. It is estimated that these systems have a probable service life in the range of 10 to 15 years.

9.7. Zinc-based Galvanic CP Systems

9.7.1. Arc-Sprayed Zinc

Three systems using arc-sprayed zinc, varying in age from 13 months to 7 years at the time of the last evaluation, were included in this study. One system was located on a structure in Texas and the other two on structures in Florida. All three systems were exposed to marine environments. Two of the three systems were installed to protect black reinforcing steel and one to protect epoxy-coated reinforcing steel.

The system installed on the Queen Isabella Causeway in Texas was 13 months old at the time of the last evaluation. It was generating an average cathodic current ranging from 1.9 to 3.8 mA/m^2 to protect black reinforcing steel The operating reference cells exhibited depolarization in excess of 100 mV in 22 hours during all evaluations.

The Howard Frankland Bridge in Tampa, Florida, was 5 years old at the time of the last evaluation; the system was applied to protect black reinforcing steel. The rebar probes were measuring on average CP current in the range of 4.72 to 5.93 mA/m^2 of steel surface area. If we assume that the concrete-to-steel surface area ratio is 2, the average current densities on the probes would translate to 2.36 to 2.87 mA/m^2. Most depolarization test results exceeded 100 mV.

The arc-sprayed zinc CP system was applied on the Seven Mile Bridge in the Florida Keys to protect epoxy-coated rebars in the columns. The system was applied at two different times. The older application was 7 years old and the newer application was 2 years old at the time of the last evaluation. In the older system, 33 to 50 percent of the depolarization test results exceeded 100 mV and, in the newer system, approximately 66 percent of the results exceeded 100 mV.

Although the theoretical service life of a 0.25-mm-thick zinc coating operating at 4 mA/m^2 at 70 percent efficiency is 30 years, no one expects it to last that long. Several factors will impact the ability of these systems to provide CP. Over time, the zinc anode is expected to passivate and stop providing the CP. Weathering of the zinc anode in the marine environment may also contribute to a reduction in service life. The consensus in the industry is that these systems may be expected to last approximately 7 to 10 years.

9.7.2. Zinc Foil with Adhesive Galvanic CP Systems

A single zinc foil with adhesive galvanic system was evaluated from the time of energization to 14 months of operation. This system was installed on pier caps of the Route 58 bridge in Henry County, Virginia. The piers are exposed to deicing salt-contaminated water runoff from leaking joints. During the evaluation period, the system provided CP current ranging from 1.66 to 4.45 mA/m^2; the embedded reference cells exhibited depolarization exceeding 100 mV in 22 hours.

The adhesive used to attach the zinc foil to the concrete surface is water soluble. It acts as an electrolyte and contains ingredients to maintain the zinc in the active state. Over time, the adhesive is expected to dry and limit the ability of the zinc to provide CP. Preliminary estimates of service life range from 7 to 10 years. Another limiting factor is the ingress of moisture in sufficient quantities into the adhesive. In the presence of moisture, the adhesive dissolves and loses its ability to provide the bond. In the system evaluated in this study, the impact of moisture ingress into the adhesive was apparent. Just after installation of the system, panels exposed to water runoff failed and a new anode had to be installed. In the 14 months of operation, failure in additional sections of the anode was observed.

9.7.3. Expanded Zinc Mesh and Bulk Anode

The prestressed piles of the Bryant Patton Bridges located at St. George Island, Florida, were protected by a combination of bulk zinc anode, expanded zinc mesh, and arc-sprayed zinc. The arc-sprayed zinc sections of the piles were not instrumented and could not be evaluated. The only mechanism to evaluate the other two anodes (bulk and expanded mesh) was to measure output current in 44 piles. The current output by the combination of the bulk and the expanded anodes resulted in output concrete current density ranging from approximately 2.5 to 3.5 mA/m^2. The current output was in the range expected from galvanic CP systems.

The combination of the bulk anode and the expanded zinc mesh anode was expected to have a service life of 15 to 20 years. This service life may be reduced by the passivation of the expanded zinc mesh anode if it is not in contact with sufficient chloride-contaminated water.

9.8. Test Methods

The secondary objective of this research was to identify the most appropriate laboratory and field test method(s) for evaluating and monitoring the performance of CP systems.

Based on the success and problems encountered in this study, the following test methods were recommended for evaluation of impressed-current and galvanic systems.

- Impressed-current Systems
  - Visual and delamination survey
  - Rectifier data (output voltage, current, and BEMF)
  - Polarization development or decay testing
  - AC resistance measurements (anode to system ground)
  - Current, null, or voltage probe readings

Electrical continuity testing and AC resistance measurements between the reference cells and reference cell grounds need to be conducted to investigate observed abnormalities.

- Galvanic System
  - Visual and delamination survey
  - System output current (via resistors, rebar probes, etc.)
  - Polarization development or decay (via embedded reference cells, rebar probes, external reference cells, etc.)
  - AC resistance measurements (anode and system ground)

Electrical continuity testing and AC resistance measurements between the reference cells and reference cell grounds need to be conducted to investigate observed abnormalities.

9.9. Problems Encountered with Test Methods

9.9.1. Electrical Continuity Testing

None of the techniques used to determine electrical continuity is reliable in the field. Each has some drawbacks or limitations. The DC technique is most widely used, but fails to detect continuity in the presence of currents flowing in the steel network. The AC resistance technique fails to detect discontinuities when capacitance between the two elements being tested allows the AC signal to short through it, and the potential technique requires the potential of the element being measured to be stable during testing. In the absence of a better technique, it is recommended that the DC technique be used. If unexpected results are obtained, AC resistance and potential technique should be used and data from all three techniques should be analyzed to detect the presence or lack of continuity.

9.9.2. Instant-Off Potential Measurement

Both the peak-hold and the manual method of measuring instant-off potentials for the impressed-current CP systems can produce erroneous results in the presence of noise and spikes generated during interruption of output current. An oscilloscope must be used if the measurements obtained with the peak-hold method and the manual method are accurate. If noise is present, the scope null method may be used to obtain more accurate instant-off potentials.

For galvanic CP systems, the manual method is most appropriate.

10.0. REFERENCES

1. Stratfull, R.F., "Experimental Cathodic Protection of a Bridge Deck," Transportation Research Board No. 500, pp. 1-15, 1974, and Federal Highway Administration Report No. FHWA-RD-74-031, January 1974, Washington, DC.

2. Barnhart, R.A., Federal Highway Administrator, Memorandum entitled "FHWA Position on Cathodic Protection Systems," April 1982, Federal Highway Administration, Washington, DC.

3. *Standard Method for Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials, T-260*, American Association of State Highway and Transportation Officials, Washington, DC, 1994.

4. *Task Force 29 Report - Guide Specifications for Cathodic Protection of Concrete Bridge Decks*, American Association of State Highway and Transportation Officials-Association of General Contractors-American Road & Transportation Builders Association (AASHTO-AGC-ARTBA), Washington, DC, 1994.

5. Corrpro Companies, "Evaluation Report for Bridge Pier Caps on I-95 over James River, Richmond, Virginia," July 1993; Strategic Highway Research Program C-102F, Washington, DC.

6. *Standard Test Methods for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete: C-876*, In *Annual Book of ASTM Standards - Construction*; American Society for Testing and Materials, Philadelphia, PA. 1991.